



GUIDELINE

ASHRAE Guideline 22-2012
Supersedes ASHRAE Guideline 22-2008

Instrumentation for Monitoring Central Chilled-Water Plant Efficiency

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NOTE

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(This foreword is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

FOREWORD

Guideline 22 was developed by ASHRAE to provide a source of information on the instrumentation and collection of data needed for monitoring the efficiency of an electric-motor-driven central chilled-water plant. A minimum level of instrumentation quality is established to ensure that the calculated results of chilled-water plant efficiency are reasonable. Several levels of instrumentation are developed so that the user of this guideline can select the level that suits the needs of each installation.

The basic purpose served by this guideline is to enable the user to continuously monitor chilled-water plant efficiency in order to aid in the operation and improvement of that particular chilled-water plant, not to establish a level of efficiency for all chilled-water plants. Therefore, the effort here is to improve individual plant efficiencies and not to establish an absolute efficiency that would serve as a minimum standard for all chilled-water plants.

It is recognized that there are different needs for monitoring the efficiency of a chilled-water plant. In most cases, the principal objective is to maintain and improve the efficiency of the chilled-water plant. There are also cases where greater accuracy is desired for monitoring chilled-water plant efficiency. The instrumentation section allows the user to determine the required accuracy for the application.

The user of this guideline should be aware that the quality of the instrumentation directly affects the results obtained and, therefore, the accuracy of the chilled-water plant efficiency. As a result, special attention should be given to the selection of instrumentation in order to ensure that the expected result is delivered.

Chilled-water plant efficiency is expressed in different terms. This guideline uses the recognized term for chilled-water plant efficiency, which is coefficient of performance (COP). While the guideline uses COP, it is understood that in areas using inch-pound (I-P) units, kW/ton is the common term for determining chilled-water plant efficiency. Appendix B of this guideline provides the information necessary to derive chilled-water plant efficiency when using kW/ton. Also, in Appendix E, an example specification is provided for designers of chilled-water plants who wish to incorporate the monitoring of COP or kW/ton into specifications for new plants or modifications of existing plants.

It should be pointed out that this guideline does not offer any information on the design of a chilled-water plant. It is applicable to all electric-motor-driven chilled-water plants regardless of their configuration or types of chillers, cooling towers, pumps, and other parasitic electric chilled-water plant loads. This guideline is designed to help plant managers and operators achieve and maintain a desired level of efficiency for their chilled-water plants.

This is a revision of ASHRAE Guideline 22-2008. This guideline was prepared under the auspices of ASHRAE. It may be used, in whole or in part, by an association or government agency with due credit to ASHRAE. Adherence is strictly on a

voluntary basis and merely in the interests of obtaining uniform standards throughout the industry.

The changes made for the 2012 revision are as follows:

- Updated references
- Minor editorial changes

1. PURPOSE

This guideline defines recommended methods for measuring chilled-water plant thermal load and energy use and for calculating chilled-water plant efficiency.

2. SCOPE

2.1 This guideline includes

- a. recommendations for methods and devices used to measure electrical usage, fluid flow, and temperature, and
- b. procedures for acquiring the necessary data and calculating system efficiency.

2.2 These procedures are for site-specific application. They do not discuss the comparison of collected data between different sites, nor do they recommend that data obtained be applied in this manner.

2.3 The procedures also do not discuss

- a. any plants except electrically driven chilled-water plants,
- b. design and operation of central chilled-water plants, except for recommending the instrumentation used to determine plant efficiency, or
- c. selection, application, or operation of system components.

3. DEFINITIONS

For the definitions of key terms used in this guideline, refer to *ASHRAE Terminology of Heating, Ventilation, Air Conditioning, and Refrigeration*.¹

4. UTILIZATION

4.1 This guideline allows the user to monitor chilled-water plant efficiency and to make modifications to the setpoints of the system such that the overall efficiency of the chilled-water plant is improved. In order to properly evaluate the efficiency of the chilled-water plant, it is first necessary to accurately measure the variables that will determine this efficiency.

The efficiency of the chilled-water plant, which is defined in this guideline as coefficient of performance (COP), is dependent upon the energy use of a number of different pieces of equipment, including, but not limited to, the following:

- chillers,
- evaporator pumps,
- condenser pumps, and
- cooling towers.

Each piece of equipment can have a significant impact on chilled-water plant efficiency.

This guideline is entirely focused on reporting the operational efficiency of existing plants. For information relating to achieving efficiency during the initial design of a chilled-water plant, refer to recognized standards such as *ANSI/ASHRAE/IESNA 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings*,² as well as to the ASHRAE Handbooks.^{3, 4, 5, 6}

Since the design and layout of chilled-water plants varies widely depending upon their specific applications, this guideline addresses common chilled-water plant layouts for instrumentation and collection of data. Applications that include thermal energy storage and heat recovery are more complex and may require a more sophisticated approach than this guideline provides. If some modification of the data collection and analysis method were made to include the additional equipment used in such applications, this variation on the methodology of this guideline could be used to give an overall chilled-water plant efficiency.

Chilled-water plant efficiency is not dependent upon any one device; rather, it is the overall match of system components that determine efficiency.

4.2 Informative Appendix E of this guideline provides a sample specification that can be used when management prefers to contract the determination of chilled-water plant efficiency to an outside vendor or agency. For this guideline to be cited in a specification, the following plant-specific information must be provided:

- Equipment whose power is to be included.
- Equipment whose power is not to be included (if any).
- Thermal cooling loads to be included.
- Thermal cooling loads not to be included (if any).
- The maximum allowable error tolerance in the result.
- A summary of how the gathered data should be stored and presented.

5. CHILLED-WATER PLANT TYPES AND INSTRUMENTATION

5.1 Primary/Secondary Chilled Water. Detailed in Figure 5-1 is an example primary/secondary chilled-water system. The diagram provides a set of typical points that could be measured to give an overall chilled-water plant COP. These points can be reduced or expanded upon as the user deems necessary.

5.2 Primary or Variable Primary Flow System. Detailed in Figure 5-2 is an example primary flow system. A system such as this normally utilizes variable-frequency drives on the chilled-water pumps, as is specified by some requirements of ANSI/ASHRAE/IESNA Standard 90.1.² The diagram provides a set of typical points that could be measured to give an overall chilled-water plant COP. These points can be reduced or expanded upon as the user deems necessary.

5.3 Instrumentation. To measure chilled-water plant efficiency, appropriate instrumentation is required to achieve the expected result of this guideline. An instrumentation table such as Table 5-1 should be used to define the instrument range, measurement range, and measurement accuracy for each piece of equipment that uses electric energy. The specific

instrument and the measurement range are dependent on the capacity of equipment for the specific chilled-water plant. See Informative Appendix A, Instrument Specifications Table, for an example of the data that should be provided in the table.

Depending on the specific application, the user may decide to measure chilled-water plant efficiency with or without the pump energy required to distribute water to the loads.

Data calculation and archiving of this data should be to one order of magnitude greater than the measurement accuracy. Operator interface display resolution should be consistent with the measurement accuracy; the recommendation of this guideline is that the resolution should be the same magnitude as the midpoint of the measured value multiplied by the accuracy.

5.4 Data Quality. The quality of any measurement is dependent upon the measurement location, the capability of the measurement sensor and the data-recording instrument, and the sampling method employed. This guideline recommends that the instrumentation selected for monitoring central chilled-water plant efficiency have the capabilities described in Sections 5.4.1 and 5.4.2 below.

Note: If pre-existing instrumentation is already installed on the equipment, one may consider making use of it. To be considered, however, such instrumentation should first meet the data integrity recommendations of this guideline and be budgeted for the added costs for calibration and maintenance that this guideline recommends.

5.4.1 Data Recording Device. The selection of a data recording device is dependent upon the following factors:

- Quality of the device (accuracy, precision, drift, rate of response).
- Quantity and type of inputs required.
- Installation restrictions.
- Signal conditioning.
- Measurement range.
- Resources available to purchase and support the device.

Digital data acquisition instrumentation is now the typical hardware of choice to gather field data. This is true whether the data is gathered by a portable instrument or by a permanently installed building automation system (BAS). However, BAS hardware is typically not designed for the kind of data acquisition this guideline recommends, and its ability must be demonstrated before it can be used with confidence (See Heinemeier et al.).⁷ Building management system (BMS) control requirements are not always compatible with measurement and monitoring requirements.

Characteristics to consider for the data recording device include:

Scan Rate. It is always best to strive for an order of magnitude higher scan rate than the period of the process being measured. This is especially true with dynamic processes.

Time Measurement Characteristics. Performance measurements are directly affected by the resolution, accuracy, and precision of the data recording device internal

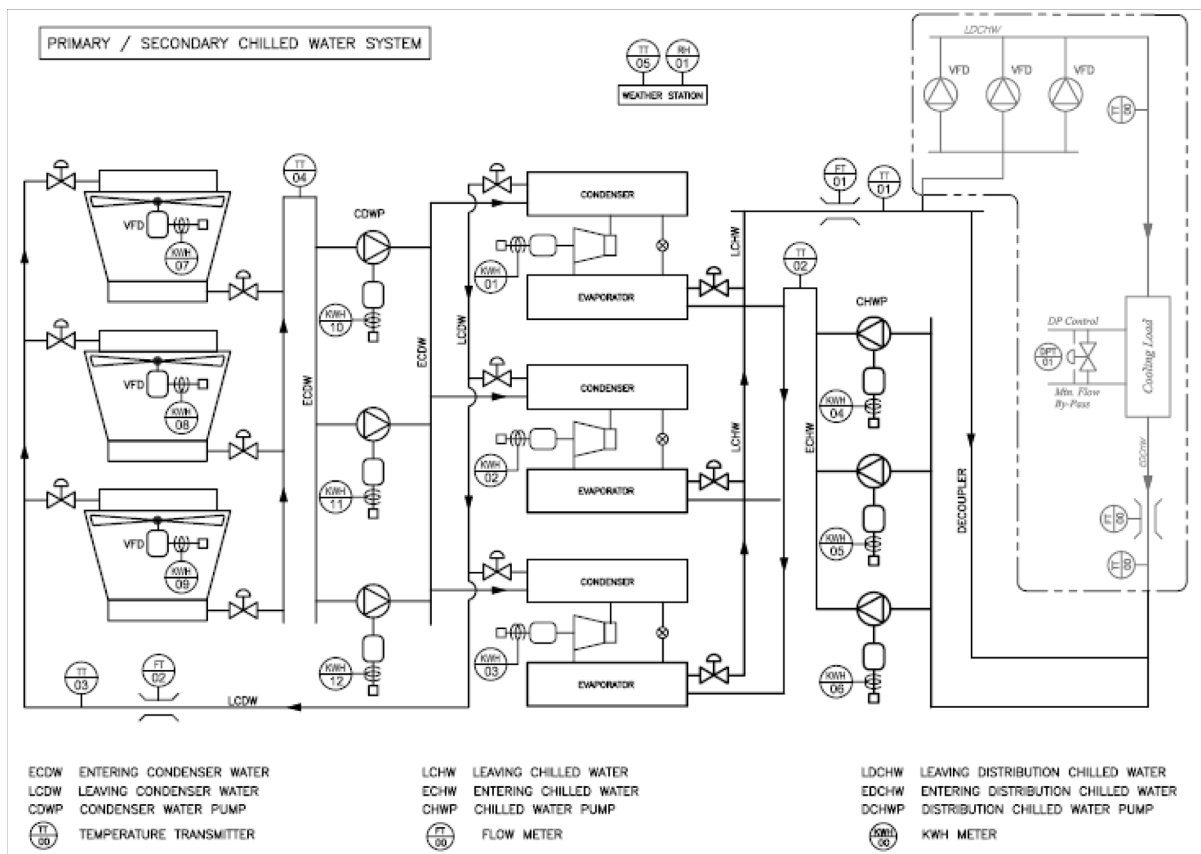


Figure 5-1 Example of primary/secondary chilled-water plant.

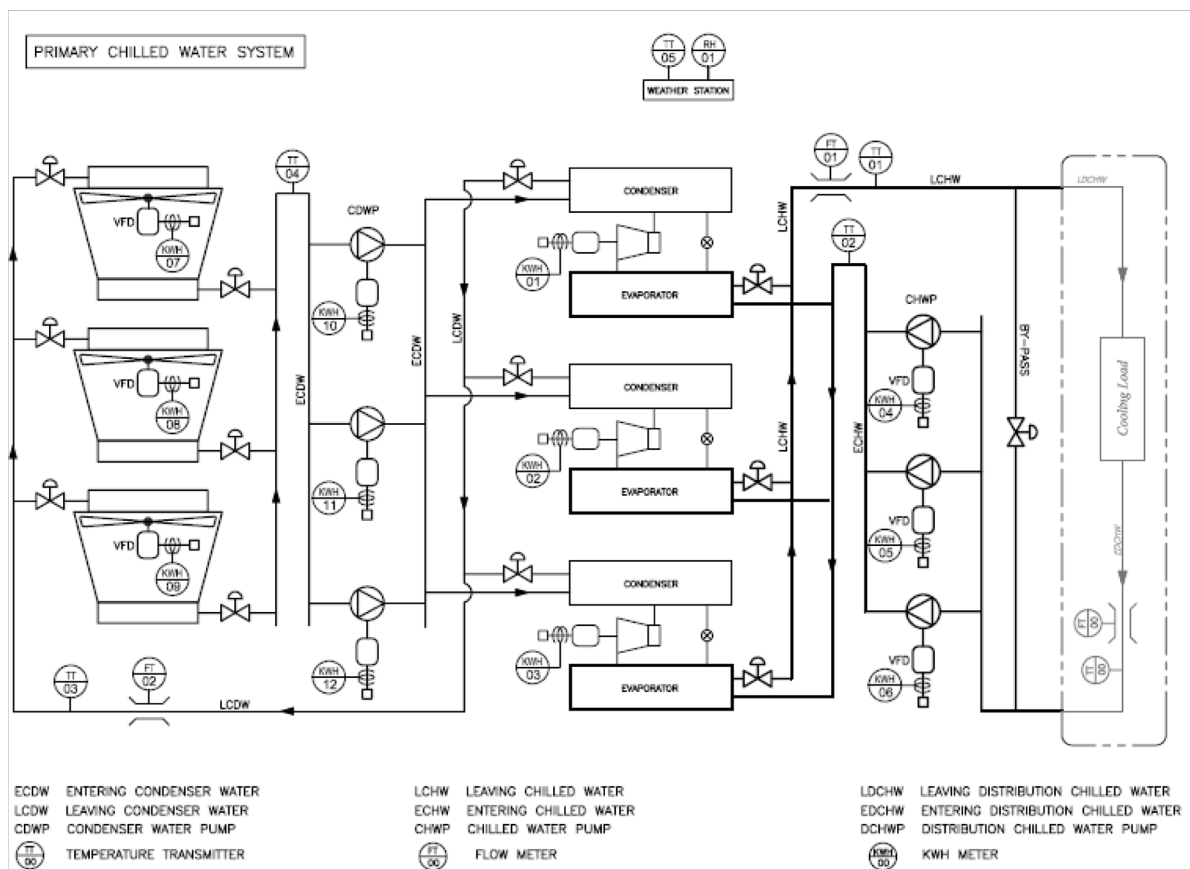


Figure 5-2 Example of primary-only chilled-water plant.

TABLE 5-1 Instrumentation Table

ID	Point Description	Measurement Range	Sensor Type or Calculation Method	Installation Location	Input Type	Instrument Range	End-to-end Accuracy (% of reading unless noted)	Data Resolution	Refresh Interval (min)	Trend Interval (min)
Power Measurements										
kW01	Chiller 1 Power									
kW02	Chiller 2 Power									
kW03	Primary ChW Pump 1 Power									
kW04	Primary ChW Pump 2 Power									
kW05	Secondary ChW Pump 3 Power									
kW06	Secondary ChW Pump 4 Power									
kW07	Chiller 1 CW Pump Power									
kW08	Chiller 2 CW Pump Power									
kW09	Cooling Tower Fan 1 Power									
kW10	Cooling Tower Fan 2 Power									
Flow Measurements										
FT01	Chilled Water Flow									
FT02	Condenser Water Flow									
TT01	Chilled Water Supply Temperature									
TT02	Chilled Water Return Temperature									
TT03	Condenser Entering Water Temperature									
TT04	Condenser Leaving Water Temperature									
TT05	Ambient Dry-Bulb Temperature									
TT06	Ambient Wet-Bulb Temperature									
Calculated Values										
CC01	ChWPlant Thermal Cooling Output									
CC02	chilled-water plant Efficiency									
CC03	Plant Heat of Rejection									

clock per unit of time. Most systems provide reasonable capabilities.

Engineering-Unit Conversion Methods. Converting of sensor output to engineering units is typically provided by most equipment utilizing the linear scalar and offset method ($y = mx + b$). Advanced systems provide for polynomial curve fitting or point-to-point interpolation. Many systems offer some form of temperature conversion tables or standard equations for resistance temperature detectors (RTDs) and/or thermocouples (TCs). Engineering units are extremely helpful in performing on-line sensor calibrations, troubleshooting, and inter-channel calculations (using concurrent data from more than one channel).

Math Functions. It is desirable to have the ability to manipulate the sampled data as it is scanned. One may also need to determine individual channel interval averages, minimums, maximums, standard deviations, and samples per interval and perform inter-channel calculations, including obtaining averages and loads. BASs typically are not provided with the ability to perform time-interval-based averaging intervals; however, some newer systems can be configured to provide the required data.

Data Archival and Retrieval Format. Most limited channel data recording devices provide for archival of averaged or instantaneous measured data in a time series record format that can be directly loaded into a spreadsheet.

In general, using a BAS as the data-recording instrument should be considered only after careful review of its capabilities. Some BASs cannot record and archive data at regular intervals; however, some newer systems can be configured to provide the required data.

5.4.2 Sensors. Sensor selection is dependent upon the quality (accuracy, precision, drift, rate of response), quantity, installation restrictions, method of measurement required, signal output requirements (or signal conditioning), measurement range, turndown, the capabilities of the intended data recording device, and the resources available to purchase and/or support it.

5.5 Calibration. It is highly recommended that instrumentation used in measuring the information required to evaluate chilled-water plant efficiency be calibrated with procedures developed by the National Institute of Standards and Technology (NIST). Primary standards and no less than third-order NIST traceable calibration equipment should be utilized wherever possible. Calibration by NIST is considered first order, an independent lab calibration against the NIST standard is second order, and a user's calibration against the independent lab instrument (a transfer standard) is considered third order.

5.6 The Uncertainty of the Measurement. It should be understood that any measurement of chilled-water plant efficiency includes a degree of uncertainty; this is true whether or not the degree of uncertainty is specifically specified. Measurements made in the field are especially subject to potential errors. In contrast to measurements made under the controlled conditions of a laboratory setting, field measurements are typ-

ically made under less predictable circumstances and with less accurate and less expensive instrumentation. Field measurements are vulnerable to errors arising from variable measurement conditions (the method employed may not be the best choice for the conditions of the specific application), from limited instrument field calibration (typically due to the fact that field calibration is more complex and expensive), from the simplified data sampling and archiving methods employed, and from limitations in the ability to adjust instruments in the field. Table 5-2 provides a range of maximum allowable measurement error requirements of individual measurements to meet a desired overall uncertainty in the resulting efficiency.

It is recommended that the installed instrumentation be capable of calculating a resultant COP within 5% of the true value. As Table 5-2 shows, only the measurement errors listed in the first three rows of the table are capable of meeting this recommendation.

See Informative Appendix C for a discussion of how the desired uncertainty in the result impacts individual sensor selection. See also *ASHRAE Guideline 14, Measurement of Energy and Demand Savings*, Annex A: Physical Measurements,⁸ for a detailed discussion of sensors, calibration techniques, laboratory standards for measurement of physical characteristics, equipment testing standards, and cost and error considerations.

TABLE 5-2 Impacts of Measurement Errors

Measurement Error (% of Reading)			Result Error (%)	
% Power (e.g., kW)	% Flow (e.g., gpm, L/s, lb/h)	% ΔT (e.g., °F, °C)	% Capacity (e.g., ton, kW, ton-h)	% COP (or kW/ton, kWh/ton-h)
1	1	2	2.24	2.45
1.5	2	2	2.83	3.20
1.5	3	3	4.24	4.50
1.5	3	4	5.00	5.22
3	5	5	7.07	7.68
3	7	7	9.90	10.34
3	7	12	13.89	14.21
3	10	10	14.14	14.46
3	10	12	15.62	15.91
3	10	15	18.03	18.28
5	15	15	21.21	21.79
5	10	20	22.36	22.91
5	7	24	25.00	25.50
5	10	25	26.93	27.39
5	15	25	29.15	29.58

6. DATA GATHERING AND TRENDING

6.1 Averaging Calculation Method. The measured values from instruments are unlikely to be constant; they can fluctuate to a greater or lesser extent depending on the installed conditions and the instrument employed. For calculation, display, and recording purposes, all data should be continuously averaged over a short time period to remove the fluctuations (“smoothing”) and provide meaningful data to work with. For more detailed information about averaging, refer to Informative Appendix D in this guideline.

7. CALCULATIONS

7.1 Computation of the Coefficient of Performance (COP)

7.1.1 For an electric-motor-driven chilled-water plant, the term *COP* is a dimensionless ratio consisting of the work done, W_d , divided by the work applied, W_a .

7.1.2 The work done, W_d , is the standard heat transfer equation for all chilled-water solutions under steady-state conditions:

For I-P units,

$$W_d = m_w \times c_p \times \Delta T \quad (\text{Btu/h}), \quad (1) \text{ (I-P)}$$

where

$$\begin{aligned} m_w &= \text{water flow rate in lb/h,} \\ c_p &= \text{specific heat at constant pressure in Btu/(lb} \cdot \text{°F), and} \\ \Delta T &= \text{temperature difference in °F.} \end{aligned}$$

For SI units,

$$W_d = m_w \times c_p \times \Delta T \quad (\text{kW}), \quad (1) \text{ (SI)}$$

where

$$\begin{aligned} m_w &= \text{water flow rate in kg/s,} \\ c_p &= \text{specific heat at constant pressure in kJ/(kg} \cdot \text{K), and} \\ \Delta T &= \text{temperature difference in °C.} \end{aligned}$$

7.1.3 The work applied, W_a , is the sum of all electrical energy inputs to the chilled-water plant:

For I-P units,

$$W_a = 3413 \times \text{kW} \quad (\text{Btu/h}), \quad (2) \text{ (I-P)}$$

where

$$W_a = \text{electrical power in kW.}$$

For SI units,

$$W_a = \text{kW} \quad (\text{kW}), \quad (2) \text{ (SI)}$$

where

$$W_a = \text{electrical power in kW.}$$

7.1.4 The basic equation for COP for all chilled-water solutions is therefore expressed as follows:

For I-P units,

$$\text{COP} = \frac{W_d}{W_a} = \frac{m_w \times c_p \times \Delta T}{3413 \times \Sigma \text{kW}} \quad (\text{dimensionless}) \quad (3) \text{ (I-P)}$$

For SI units,

$$\text{COP} = \frac{W_d}{W_a} = \frac{m_w \times c_p \times \Delta T}{\Sigma \text{kW}} \quad (\text{dimensionless}) \quad (3) \text{ (SI)}$$

7.2 Determination of COP for Chilled-Water Plants Utilizing Standard Water

7.2.1 Chilled-water plants in US locations measure the flow rate, ω , in gallons per minute (gpm).

For I-P units, therefore,

$$\omega = \frac{m_w}{8.34 \text{ lb/gal} \times 60 \text{ min/h}} = \frac{m_w}{500}; \text{ or } m_w = 500\omega, \quad (4) \text{ (I-P)}$$

where ω is flow in gpm.

For S-I units,

$$\text{L/s} = \omega = m_w, \quad (4) \text{ (SI)}$$

where ω is flow in L/s.

7.2.2 For I-P units, although the specific heat, c_p , for pure water at temperatures from 40°F to 60°F ranges from 1.006 to 1.002, it is generally accepted as 1.0 for standard water at these temperatures. For SI units, although the specific heat, c_p , for pure water at temperatures from 4.44°C to 15.55°C ranges from 4.203 to 4.185 kJ/(kg·K), it is generally accepted as 4.19 kJ/(kg·K) for standard water at these temperatures.

7.2.3 The differential temperature, ΔT , for chilled-water plants is the difference between the temperature of the water returning to the plant from the distribution system, T_2 , and the water supplied by the chilled-water plant to the distribution system, T_1 .

7.2.4 The equation for COP_w for a chilled-water plant utilizing standard water is therefore expressed as follows:

For I-P units,

$$\begin{aligned} \text{COP}_w &= \frac{500 \times \omega \times 1 \times (T_2 - T_1)}{3413 \times \Sigma \text{kW}} \\ &= \frac{\omega \times (T_2 - T_1)}{6.826 \times \Sigma \text{kW}} \quad (\text{dimensionless}) \end{aligned} \quad (5) \text{ (I-P)}$$

For SI units,

$$\text{COP}_w = \frac{\omega \times 4.19 \times (T_2 - T_1)}{\Sigma \text{kW}} \quad (\text{dimensionless}) \quad (5) \text{ (SI)}$$

7.3 Determination of COP for Chilled-Water Plants Utilizing Other Solutions of Water

7.3.1 Solutions of water and chemicals are used in chilled-water plants to alter the freezing point. For I-P units, typical solutions are the glycols that have specific gravities greater than 1 and specific heats less than 1. Equation 5 (I-P) can be altered for glycols (or other solutions) since all specific gravities used herein are related to that for water.

For I-P units, therefore,

$$\text{COP}_g = \frac{\omega_s \times s_g \times c_{pg} \times (T_2 - T_1)}{6.826 \times \Sigma \text{kW}}, \quad (6) \text{ (I-P)}$$

where

- ω_s = flow of the glycol solution in gpm,
- s_g = specific gravity of the glycol solution (dimensionless), and
- c_{pg} = specific heat of the glycol solution in Btu/(lb·°F).

For SI units, specific gravities are greater than 1 and specific heats less than 4.19 kJ/kg. Equation 5 (SI) can be altered for glycols since all specific gravities used herein are related to that for water.

For SI units, therefore,

$$\text{COP}_g = \frac{\omega_s \times \rho \times c_{pg} \times (T_2 - T_1)}{1000 \times \Sigma \text{kW}}, \quad (6) \text{ (SI)}$$

where

- ω_s = flow of the glycol solution in L/s,
- ρ = density of the glycol solution in kg/m³, and
- c_{pg} = specific heat of the glycol solution in kJ/(kg·K).

Note: See Informative Appendix B of this guideline for the determination of kW/ton for electric-motor-driven chilled-water plants.

8. REFERENCES

- ¹ASHRAE *Terminology of Heating, Ventilation, Air Conditioning, and Refrigeration*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 1991.
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- ⁸ASHRAE *Guideline 14-2002, Measurement of Energy and Demand Savings*, Annex A, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2002.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX A—EXAMPLE INSTRUMENT SPECIFICATION TABLE

TABLE A-1 Example Instrument Specification Table

ID	Point Description	Measurement Range	Sensor Type or Calculation Method	Installation Location	Input Type*	Instrument Range	End-to-End Accuracy (% of reading unless noted)	Data Resolution	Refresh Interval (min)	Trend Interval (min)
Power Measurements										
5	Chiller 1 Power	30 to 288 kW	True root-mean-square (RMS), three-phase, integrated equipment, stand-alone analog output or networked power meter		AI	0 to 300 kW	±1.0%	0.1 kW	1	1
6	Chiller 2 Power	30 to 288 kW	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter		AI	0 to 300 kW	±1.0%	0.1 kW	1	1
7	Primary Chilled-Water Pump 1 Power	12 to 15 kW	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter		AI	0 to 25 kW	±1.0%	0.01 kW	1	1
8	Primary Chilled-Water Pump 2 Power	12 to 15kW	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter		AI	0 to 25 kW	±1.0%	0.01 kW	1	1
9	Secondary Chilled-Water Pump 3 Power	2 to 10 kW	Variable-frequency-drive (VFD) bus output for kW		AI	0 to 25 kW	±3.0%	0.01 kW	1	1
10	Secondary Chilled-Water Pump 4 Power	2 to 10 kW	VFD bus output for kW		AI	0 to 25 kW	±3.0%	0.01 kW	1	1
11	Chiller 1 Chilled-Water Pump 5 Power	50 to 54 kW	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter		AI	0 to 75 kW	±1.0%	0.01 kW	1	1
12	Chiller 2 Chilled-Water Pump 6 Power	50 to 54 kW	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter		AI	0 to 75 kW	±1.0%	0.01 kW	1	1
24	Cooling Tower Fan 1 Power	5 to 22 kW	VFD bus output for kW		DI	0 to 25 kW	±3.0%	0.01 kW	1	1
25	Cooling Tower Fan 2 Power	5 to 22 kW	VFD bus output for kW		DI	0 to 25 kW	±3.0%	0.01 kW	1	1

*AI = analog input; DI = digital input; C = calculated value; #C4 = constant for converting chilled-water flow times ΔT to tons; #C5 = constant for converting condenser water flow times ΔT to tons.

TABLE A-1 Example Instrument Specification Table (continued)

ID	Point Description	Measurement Range	Sensor Type or Calculation Method	Installation Location	Input Type*	Instrument Range	End-to-End Accuracy (% of reading unless noted)	Data Resolution	Refresh Interval (min)	Trend Interval (min)
Flow Measurements										
26	Chilled-Water Flow	800 to 2400 gpm	Hot tapped insertion vortex shedding		AI	0 to 3000 gpm	±3.0% 1 to 15 ft/min	1 gpm	1	1
27	Condenser Water Flow	1000 to 3000 gpm	Hot tapped insertion vortex shedding		AI	0 to 4000 gpm	±3.0% 1 to 15 ft/min	1 gpm	1	1
Temperature Measurements										
32	Chilled-Water Supply Temperature	38 to 55°F	1000 ohm thermistor or resistance temperature detector (RTD)		AI	35 to 75°F	±0.2°F	±0.01°F	1	1
33	Chilled-Water Return Temperature	42 to 60°F	1000 ohm thermistor or resistance temperature detector (RTD)		AI	35 to 75°F	±0.2°F	±0.01°F	1	1
34	Condenser Entering Water Temperature	55 to 90°F	1000 ohm thermistor or resistance temperature detector (RTD)		AI	50 to 110°F	±0.2°F	±0.01°F	1	1
35	Condenser Leaving Water Temperature	55 to 100°F	1000 ohm thermistor or resistance temperature detector (RTD)		AI	50 to 110°F	±0.2°F	±0.01°F	1	1
42	Ambient Dry-Bulb Temperature	32 to 110°F	In weather station in fully shaded location or ventilated enclosure		AI	-20 to 140°F	±0.3°F	±0.01°F	1	5
43	Ambient Wet-Bulb Temperature	20 to 85°F	In weather station in fully shaded location or ventilated enclosure		AI	0 to 100°F	±0.3°F	±0.01°F	1	5
Calculated Values										
51	Chilled-Water Plant Thermal Cooling Output	50 to 1000 tons	(Difference of 2 measured values) [#33, #32] multiplied by measured value [#26] multiplied by a constant #C4*		C	N/A	±3% tons	0.1 tons	1	5
54	Chilled-Water Plant Efficiency	0.3 to 0.8 kW/ton	(Sum of measured values) [#5, #6, #49a, #49b, #9, #10, #24, #25] divided by calculated value [#51]		C	N/A	±5% kW/tons	0.01 kW/ton	1	5
55	Chilled-Water Plant Heat of Rejection	0 to 1300 tons	(Difference of 2 measured values) [#35, #34] multiplied by measured value [#27] multiplied by a constant #C5*		C	N/A	±3% tons	0.1 tons	1	5

*AI = analog input; DI = digital input; C = calculated value; #C4 = constant for converting chilled-water flow times ΔT to tons; #C5 = constant for converting condenser water flow times ΔT to tons.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX B— DETERMINATION OF kW/ton

B1. DETERMINATION OF kW/ton

B1.1 A popular measurement of energy consumption in areas using I-P units for an electric-motor-driven chilled-water plant is kW/ton, where the total energy consumption in kWh is divided by the ton-hours of cooling generated by that plant. It is the inverse of COP since it is the work applied, W_a , divided by the work done, W_d . The work applied is merely the sum of the kWh consumed by the chilled-water plant. The work done is determined in ton-hours of cooling. One ton-hour of cooling is equal to 12,000 Btu/h, so:

$$W_d = \frac{m_w \times c_p \times \Delta T}{12,000} \text{ (tons)} \quad (\text{B-1})$$

B1.2 The kW/ton for all water solutions is therefore:

$$\frac{W_a}{W_d} = \frac{\Sigma kW}{\left(\frac{m_w \times c_p \times \Delta T}{12,000} \right)} \text{ (kW/ton)} \quad (\text{B-2})$$

B1.3 For most chilled-water plants using standard water, Equation B-1 is changed by substituting ω with $500 \times Q_w$ in Equation B-2 and changing c_p to 1.0. Therefore:

$$\frac{\Sigma kW}{\left(\frac{500 \times \omega \times \Delta T}{12,000} \right)} = \frac{24 \times \Sigma kW}{\omega \times \Delta T} \text{ (kW/ton)}$$

Substituting $(T_2 - T_1)$ for ΔT yields

$$\text{kW/ton}_w = \frac{24 \times \Sigma kW}{\omega \times (T_2 - T_1)} \text{ (Kw/ton)} \quad (\text{B-3})$$

B1.4 It is often desirable to convert one of the two terms, kW/ton or COP, to the other. This is done by making a constant κ equal to $Q_w \times (T_2 - T_1) \div \Sigma kW$. Now Equation 5 for COP_w in Section 7.2.4 becomes $\kappa \div 6.826$ and Equation B-3 for kW/ton_w becomes $24 \div \kappa$. Solving for κ results in

$$\kappa = 6.826 \times \text{COP}_w = 24 \div \text{kW/ton}_w$$

$$\text{or} \quad \text{COP}_w = \frac{3.517}{\text{kW/ton}_w} \text{ or } \text{kW/ton}_w = \frac{3.517}{\text{COP}_w} \quad (\text{B-4})$$

B1.5 Equation B-4 is applicable to all water solutions, including glycols.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX C—UNCERTAINTY IMPACTS ON MEASUREMENT REQUIREMENTS

The material for this appendix is taken largely from a paper written by Stephen Treado and Todd Snouffer in 2001 entitled “Measurement Considerations for the Determination of Central Plant Efficiency.” It was published in *ASHRAE Transactions* 107(1):401.^{C-1}

C1. INTRODUCTION

In order to evaluate chiller efficiency and operate the chiller at its highest efficiency, it is necessary to accurately measure the variables that determine chiller efficiency and to have the capability of modifying control points to manipulate operating efficiency (Kaya 1991).^{C-2}

Chilled-water plants are rarely instrumented to provide an efficiency measurement. However, if the boundaries of the central plant control volume are taken in their broadest sense, several electrical power measurements must be made, and chilled-water measurements must be made at the inlet and outlet of the chilled-water distribution system. For rating purposes, the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) has developed a standard for measuring full-load and part-load chiller efficiency (AHRI 550/590).^{C-3} This standard specifies the operating conditions, including cooling capacity and chilled-water temperatures. While efficiencies measured using this procedure may be valid, they may not be indicative of the chiller efficiency that might be obtained in actual practice due to differences in operating conditions (Austin 1991; Schwedler 2003).^{C-4, C-5}

C2. MEASUREMENT EQUIPMENT

C2.1 Electrical Power. The accurate measurement of electrical power usually presents the least challenge in terms of resolution, accuracy, and reliability. Appropriate sensors and transducers are commercially available covering a wide range of voltage and current inputs. It is important that the measurement system give an accurate indication of true RMS power, including any effects of power factor. Care must be taken to ensure that the sensors and transducers are capable of accurately measuring the frequencies at which the equipment is operating, including any significant harmonic content. The primary consideration in this regard is the fundamental frequency of the electrical power input, which is typically 50 or 60 Hz but may vary for different equipment depending upon the location of the power sensing elements. Accuracies of better than 1% are reasonably achievable with newer instrumentation.

C2.2 Temperature. The primary temperature measurements for determining cooling capacity are the supply and return chilled-water temperatures. In addition, in order to provide information for chiller operation and optimization, condenser water temperature, outdoor dry- and wet-bulb temperatures, and evaporator refrigerant temperature may also be needed. These parameters are useful for the determi-

nation of the most efficient operating condition for a chilled-water system.

Temperature sensors can be located in wells inside water piping. Air temperature measurements require adequate shielding from radiation. If long sensor leads are anticipated, it may be desirable to connect the temperature sensors to transmitters that provide a 4-20 mA output to the central control system. This approach may also simplify wiring by reducing the number of signal leads required.

Temperature instrumentation should be installed close to the upstream (inlet) of temperature-changing devices such as chillers and cooling towers but as far downstream (outlet) as practical to ensure any temperature stratification in the outflow is well mixed.

Several types of temperature sensors are available for these applications. Following are examples listed from the least accurate to the most accurate.

C2.2.1 Thermocouples have been utilized extensively and have the advantage of being rugged, self-powered, relatively low in cost, stable, and durable. The disadvantages of thermocouples are the need for temperature compensation and a relatively large uncertainty of approximately 0.6°C (1°F).

Greater accuracy in the measurement of temperature difference can be obtained through the use of a differential thermopile consisting of a series of thermocouple junctions. An uncertainty of 0.1°C (0.18°F) is possible. While not as commonly encountered as other temperature sensing systems, this arrangement provides several advantages. First, the magnitude of the electrical signal produced by a thermopile is greater than from a single thermocouple since each pair of junctions contributes to the thermopile voltage, thereby multiplying the output in proportion to the number of thermocouple junctions. Second, the array of junctions can be distributed over a cross section of the flow area, giving a more accurate indication of average temperature in cases where the fluid temperature is not uniform. Third, temperature compensation is not required for a thermopile since temperature difference, and not absolute temperature, is being measured. The conversion of thermopile voltage to temperature is nearly linear over typical temperature ranges for these applications. However, there still may be a need to know the absolute fluid temperature in order to evaluate thermal properties, such as specific heat, and to provide operational information.

C2.2.2 Resistance temperature detectors (RTDs) are also very accurate and nearly linear over typical temperature ranges of interest for these applications. They also require excitation voltages and are considerably more expensive than either thermocouples or thermistors. With proper calibration, uncertainties of better than 0.1°C (0.18°F) can be achieved.

C2.2.3 Thermistors provide greater sensitivity and accuracy but are more costly. Thermistors require an external excitation circuit so that their resistance can be determined by measuring the voltage drop and current flow. Temperature measurement accuracy is limited by the ability to measure the voltage drop across the thermistor and current flow. The thermistor itself can be calibrated to an uncertainty of 0.001°C (0.0018°F). The calibration must be performed at a minimum of three temperatures to enable an adequate curve fit for the

temperature/resistance characteristics. With this procedure, system measurement uncertainties of better than 0.1°C (0.18°F) are easily obtained.

C2.3 Chilled-Water Flow Rate. The measurement of chilled-water flow rate is the most difficult task in the process of determining chiller efficiency. That is because flow measurements are typically invasive and because flow rate is not uniform over most flow cross sections. The measurement of fluid flow generally requires consideration of adequate runs of straight pipe or duct and minimization of turbulence-inducing elements. Calibration of flow rate measurement systems is also a tricky prospect, since flow characteristics may differ between the calibration and the actual installation. The effect of this is that factory calibrations may not be sufficiently accurate for field installations, necessitating additional field calibrations using transfer standards. In addition, some flowmeters create additional pressure losses, thereby affecting system performance and reducing efficiency.

While laboratory flow measurement uncertainties of 1% or better are possible, field measurement accuracy will likely be less, with uncertainties of 5% or greater commonly encountered.

The selection of the appropriate flow sensor depends on a number of factors, including the magnitude of the flow rate, flow velocity, pipe size and type, as well as cost considerations. Since only a few flow sensors are required, cost may not be a major concern. Durability and reliability are important considerations, and, in this regard, ultrasonic and pressure drop meters may be of some advantage.

Meter calibration and installation are important issues for flowmeters. Sensing elements must be installed in accordance with manufacturers' instructions, including consideration of requirements for straight lengths of pipe and flow straightening. Calibration can be accomplished by means of a transfer standard or by direct measurement. Flow conditions at calibration should closely match the conditions of use. Care must be taken to account for any effects of fluid properties, meter orientation, and flow disturbances, such as tees or bends. See *ASHRAE Guideline 14-2000, Measurement of Energy and Demand Savings*, Annex A1.5, Liquid Flow,^{C-6} for a description of the various types of flowmeters.

C3. CALIBRATION ISSUES

All sensors should be calibrated before installation unless an in-situ calibration is to be conducted. Manufacturers' calibration data may be sufficient as long as the installation conditions match the conditions of calibration. Manufacturers' calibration data should include documents of traceability to the calibration facility and, ultimately, traceability to national standards, typically NIST standards.

Periodic calibration checks and recalibration may be required for measurement sensors. In addition, the entire measurement system must be maintained in proper calibration, including not only the sensing elements but also voltage and current measurement devices and analog to digital converters. System calibrations should be checked on a regular basis. It is also useful to make a determination of measurement

uncertainty in order to place error bands on chiller efficiency measurements.

Sensor calibrations may not be simply single values but may be functions of the ambient conditions or the state of the measured media. For this reason, supporting measurements may be necessary to allow the determination of the primary measurement value.

C4. MEASUREMENT RESOLUTION, ACCURACY, AND UNCERTAINTY

Three related parameters that can be used to describe the capabilities of a measurement system are resolution, accuracy, and uncertainty. Resolution is the smallest change in the measured quantity that can be detected. Accuracy is the capability to indicate the true value of the measured quantity, while uncertainty is the estimated value for the error in a measured quantity, i.e., the difference between the measured value and the true value. The overall resolution and error in the determination of chiller efficiency involves the individual sensor characteristics and the form of the relation used to compute chiller efficiency.

Resolution is a function of sensitivity or responsivity of the sensor and the characteristics of the readout device. Obviously, the resolution should be sufficient to provide the required accuracy, but typically resolution will exceed absolute accuracy. Resolution should never be mistaken for accuracy, however, since accuracy is limited by the uncertainty of the measurement, not the minimum resolvable measurement increment. Measurement accuracy is determined by the measurement uncertainty. Uncertainty includes both systematic offset (bias) and random errors (precision). Calibration can help reduce bias, while random errors can be treated using statistical methods.

The required measurement accuracy is determined by the eventual use of the efficiency data. If the range of expected efficiency values is narrow and it is desired to be able to distinguish between small differences in efficiency, then obviously high accuracy is required. For example, if chiller efficiency is expected to vary by only 10% over the full range of operating conditions, then a measurement uncertainty of only 1% might not be acceptable since this would represent one-tenth of the full range. Since chiller efficiency tends to be in the range of 3 to 7 COP (0.5 to 1 kW/ton), a measurement uncertainty of 1% of the reading would represent about 0.05 COP (0.01 kW/ton).

The contribution of the individual uncertainties to the overall measurement error, in terms of probable errors, can be computed using the root-sum square formula, as follows:

$$Error_{rms} = \left(\sum \left(u_N \frac{\partial \eta}{\partial N} \right)^2 \right)^{1/2} \quad (C-1)$$

where

- u_N = individual uncertainty of variable N
- $\frac{\partial \eta}{\partial N}$ = partial derivative of efficiency with respect to variable N
- N = mass flow rate, electrical power input, or temperature difference

For each sensor, the maximum individual uncertainty, given a desired overall uncertainty for chiller efficiency of u_o , can be found from the following equation:

$$u_N = \frac{u_o}{\sqrt{3} \left(\frac{\partial \eta}{\partial N} \right)} \quad (\text{C-2})$$

This relation provides the accuracies needed for individual measurements in order to achieve the desired overall accuracy; however, accuracy trade-offs can be made to achieve the same overall uncertainty. Thus, for example, a smaller uncertainty in the electrical power measurement will allow a larger uncertainty in the flow measurement while still meeting the overall measurement accuracy goal.

The following examples use a chiller from the NIST central plant to illustrate the uncertainty analysis. The individual uncertainties shown are sample values.

Example 1

Chiller electrical power $E = 2100 \text{ kW} \pm 2.1 \text{ kW}$ ($\pm 0.1\%$ of reading)

Chilled-water flow rate $\omega = 7000 \text{ gpm} \pm 210 \text{ gpm}$ ($\pm 3.0\%$ of reading) or $3.5 \times 10^6 \text{ lb/h} \pm 105,000 \text{ lb/h}$

Temperature change of chilled water $\Delta T = 12^\circ\text{F} \pm 0.1^\circ\text{F}$ ($\pm 0.8\%$ of reading)

From Equation B-3, the chiller efficiency is 5.86 COP (0.6 kW/ton). From Equation C-1, the average root-sum square error is 0.182 COP (0.0190 kW/ton) or 3.1%.

Example 2

Using conditions similar to those in Example 1, assume that conditions produce a smaller ΔT . It is assumed that the actual performance is worse than in Example 1. How does this affect the uncertainty requirements for each measurement?

Chiller electrical power $E = 1400 \text{ kW} \pm 1.4 \text{ kW}$ ($\pm 0.1\%$ of reading)

Chilled-water flow rate $\omega = 7000 \text{ gpm} \pm 210 \text{ gpm}$ ($\pm 3.0\%$ of reading) or $3.5 \times 10^6 \text{ lb/h} \pm 105,000 \text{ lb/h}$

Temperature change of chilled water $\Delta T = 6^\circ\text{F} \pm 0.1^\circ\text{F}$ ($\pm 1.7\%$ of reading)

From Equation B-3, the chiller efficiency is 4.4 COP (0.8 kW/ton). From Equation C-1, the average root-sum square error is 0.152 COP (0.028 kW/ton) or 3.5%

Example 3

Using similar conditions as in Example 1, assume that the chiller is provided with one-half of its typical flow. It is assumed that the actual performance is close to that in Example 1. How does this affect the uncertainty requirements for each measurement?

Chiller electrical power $E = 1100 \text{ kW} \pm 1.1 \text{ kW}$ ($\pm 0.1\%$ of reading)

Chilled-water flow rate $\omega = 3500 \text{ gpm} \pm 105 \text{ gpm}$ ($\pm 3.0\%$ of reading) or $1.75 \times 10^6 \text{ lb/h} \pm 52,500 \text{ lb/h}$

Temperature change of chilled water $\Delta T = 12^\circ\text{F} \pm 0.1^\circ\text{F}$ ($\pm 0.8\%$ of reading)

From Equation B-3, the chiller efficiency is 5.60 COP (0.628 kW/ton). From Equation C-1, the average root-sum square error is 0.174 COP (0.020 kW/ton) or 3.1%

For an example of the effects of energy use, ΔT , and variable flow for both COP and kW/ton calculations, please see "Guideline 22 Appendix C Uncertainty Table.xls." This file can be downloaded for free from the ASHRAE Web site at <http://www.ashrae.org/G22>.

C5. REFERENCES FOR APPENDIX C

- C-1 Treado, S., and T. Snouffer, Measurement considerations for the determination of central plant efficiency, *ASHRAE Transactions* 107(1):401, 2001.
- C-2 Kaya, A. Improving efficiency in existing chillers with optimization technology. *ASHRAE Journal* 33(10):30–38, 1991. See also Nugent, D., 1999, *High efficiency chillers (Internet article)*.
- C-3 AHRI Standard 550-2003, *Centrifugal or Rotary Screw Water-Chilling Packages*, Air-Conditioning, Heating, and Refrigeration Institute, Arlington, VA, 2003.
- C-4 Austin, S., Optimum chiller loading, *ASHRAE Journal* 33(7):40–43, Oct. 1991.
- C-5 Schwedler, M. Take it to the limit... or just halfway, *ASHRAE Journal* 40(7):32–33, 36–39, 1998.
- C-6 *ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX D— DATA GATHERING AND TRENDING

D1. AVERAGING CALCULATION METHOD

The measured value from instruments is unlikely to be constant and can fluctuate to a greater or lesser extent depending on the installed conditions and the instrument employed. For calculation, display, and recording purposes, all data should be continuously averaged over a short time period to remove the fluctuations (a calculation method commonly referred to as “smoothing”) and provide meaningful data to work with. This has the benefit that the information will more truly reflect the true operating conditions of the plant. The following describes a method that can be used to provide smoothed data.

Once during each “trend interval,” calculate the instantaneous COP (kW/ton).

Then average the current instantaneous value into the current average with a weight of approximately 1/4 according to the following formula:

$$\text{COP (kW/ton)} = \frac{[3 \times \text{COP (kW/ton)} + \text{Current COP (kW/ton)}]}{4}$$

- Decreasing the current interval weighting is accomplished by increasing the value of the multiplier (shown as “3” in the above expression) and the divisor (shown as “4” in the above expression). The multiplier is always 1 less than the divisor.
- Increasing the current interval weighting is accomplished by decreasing the value of the multiplier and the divisor (the multiplier is always 1 less than the divisor).

For greater stability, decrease the weighting of the current interval’s instantaneous COP (kW/ton). For more definition and granularity, increase its weighting.

D2. DATA DISPLAY AND SHORT-TERM TRENDS

The COP (kW/ton) value is displayed on the chiller plant operation workstation plant graphics. It is also recommended that the COP (kW/ton) be averaged over five-minute intervals; record these values on the data recording device and trend for a minimum of seven days along with outdoor air temperature (OAT), wet-bulb temperature (calculated from OAT and outdoor air humidity [OAH]), plant power input (kW), and plant output (tons or kW).

D3. DATA RECOMMENDED FOR TRENDING OVER ENTIRE LIFE CYCLE OF PLANT

Note that the following values are intended for performance oversight and are trended in addition to normal equipment operating trends.

1. Average day’s outdoor air temperature (obtain the outside air temperature every 30 minutes and find the average of these samples each day)
2. Day’s high temperature
3. Day’s low temperature
4. Day’s high wet-bulb temperature (calculate from OAT and OAH)
5. Chilled-water supply temperature (average, max and min if chilled-water temperature is not fixed)
6. Total ton-hours (kWh) production of chilled water for the day
7. Total kWh power input for each component for the day
8. Average kW/ton (COP) for the plant for the day

It is also recommended that this daily data be recorded and archived for the entire life of the plant.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX E— EXAMPLE SPECIFICATION LANGUAGE

This sample contract language is provided for the convenience of users who desire to hire an outside agency or vendor to install the instrumentation for monitoring the efficiency of a central chilled-water plant. The sample language and example tables must be modified to fit the user's particular needs and specific chilled-water plant. Although this contract is primarily written in mandatory language (e.g., "shall"), its use is not required to meet the recommendations of this guideline.

I. Work Included

- A. The contractor shall provide equipment, software, installation, programming, functional testing, documentation, training, and training documentation capable of meeting the performance monitoring requirements listed below.

II. System Description

- A. The performance monitoring system is intended to provide in-house operators and facilities staff with the means to easily assess the current and historical performance of the facility's chilled-water system and components with respect to the performance metrics listed in Section III.
- B. The performance monitoring system shall include instrumentation, data communication hardware and software, and additional programmed and operational software capable of collecting and archiving all data sufficient to generate, visualize, and report the performance metrics listed in Section III.
- C. The performance monitoring system shall include software for analyzing and displaying both measured and calculated data as described in Section VII.
- D. The quality of any measurement is determined by the attributes of the sensor, any signal conditioning (if present), the data acquisition system and the wiring connecting them, any calibration corrections that are applied, the sensor installation, and field conditions. Accuracy, precision, linearity, drift or stability over time, dynamic or rate of response, range, turn-down, sample or scan rate, resolution, signal-to-noise ratio, engineering unit conversion and math functionality, and data storage and retrieval frequency are all terms used to describe the quality of the measurement system and its components. The level of measurement rigor required in this specification is intended to provide sufficient data quality over time for identifying/establishing the specified performance metrics and benchmarks. Through-system measurement accuracy goals for individual measurement points and metrics are as shown in Table E-1. Individual instrumentation requirements are provided in order to meet these goals.

**TABLE E-1 Through-System
Measurement Accuracy Goals**

Measurement Point or Metric	Accuracy Goal
Outside ambient temperature (°F)	0.2°F
Outside ambient wet-bulb temperature (°F)	0.2°F
Water temperature (°F)	0.1°F, if $\geq 5^\circ\text{F } \Delta T$
Water delta temperature (°F)	2% of reading
Water flow (gpm)	2% of reading, if $>1\text{--}15\text{ fps}$
Power (kW)	1.5% of reading
Chiller cooling output (tons)	3% of reading
Chiller cooling energy (ton-hrs)	3% of reading
Electric energy use (kWh)	3% of reading
Chiller performance (kW/ton)	4% of reading
Chilled-water plant performance (kW/ton)	4% of reading

III. Performance Metrics and Data Points

- A. The primary purpose of the performance monitoring system is to provide facility managers and operators with easily interpreted feedback on the current and historical performance of the facility chilled-water system. To this end, this section defines those aspects of performance that must be measured, calculated, and reported. The defined aspects of performance are referred to here as *performance metrics*. Each key performance metric is defined below, along with the control data points that are necessary for calculating and reporting each metric. Instrumentation requirements, point names, and calculation methods are specified in Section IV.
- B. To be of optimum use to building managers and operators, the performance monitoring system should also provide benchmarks that define the range of expected performance for each performance metric.
- C. *Chiller Efficiency (kW/ton)*: Instantaneous power input per cooling output of each chiller. The objective is to achieve accuracy better than $\pm 2\%$ for the kW/ton. This performance metric requires the following performance metrics and data points.
 1. *Chiller Power (kW)*: Instantaneous chiller power input.
 2. *Chilled-Water Output (tons)*: Instantaneous chilled-water cooling output from chiller.
- D. *Chilled-Water Plant Efficiency (kW/ton)*: Instantaneous power input per cooling output versus required load. The objective is to achieve accuracy better than $\pm 4\%$ for the kW/ton for the chilled-water plant. This performance metric requires the following performance metrics and data points.
 1. *Chilled-Water Plant Power (kW)*: Instantaneous chiller, chilled-water pumps (including primary, secondary, and others, if applicable), tower fans, and condenser water pumps power inputs.

2. *Chilled-Water Plant Thermal Cooling Output (tons)*: Instantaneous chilled-water plant cooling output.
- E. *Average Chilled-Water Plant Thermal Cooling Output (tons)*: 30-minute running average of the instantaneous chilled-water plant thermal cooling output.
- F. *Maximum Average Chilled-Water Plant Thermal Cooling Output (tons)*: Maximum 30-minute running average of the instantaneous chilled-water plant thermal cooling output. Provide maximums for daily, monthly, and yearly time intervals.
- G. *Daily Chilled-Water Plant Thermal Cooling Energy (ton-hours)*: Total chilled-water plant thermal cooling output provided in a 24-hour period.
- H. *Maximum Daily Chilled-Water Plant Thermal Cooling Energy (ton-hours)*: Maximum 24-hour total chilled-water plant thermal cooling output. Provide maximums for daily, monthly, and yearly time intervals.
- I. *Site Weather*: On-site outdoor ambient air temperatures obtained external to the building.
 1. Outdoor ambient air dry-bulb temperature (°F)
 2. Outdoor ambient air wet-bulb temperature (°F)

IV. Instrumentation and Data Requirements

A. Liquid Flowmeters

1. Each flowmeter shall have a rated instrument accuracy within $\pm 1\%$ of reading from 3.0 through 30 fps and $\pm 2\%$ of reading from 0.4 through 3.0 fps velocity. Precision shall be within $\pm 1.0\%$ of reading. Resolution of any signal conditioning and readout device shall be within $\pm 0.1\%$ of reading. The instrument shall be capable of measuring flow within the stated accuracy over the entire range of flow. Flowmeters shall be rated for line pressure up to 400 psi. These requirements include the sensor and any signal conditioning.
2. Each flowmeter shall be individually wet calibrated against a volumetric standard accurate to within 0.1% and traceable to the National Institute of Standards and Technology (NIST). Flowmeter accuracy shall be within $\pm 0.5\%$ at calibrated typical flow rate. A certificate of calibration shall be provided with each flowmeter.
3. When dictated by multiple elbows and other disturbances upstream and short available pipe runs, the flow measurement station shall provide compensation for rotational distortion in the velocity flow profile.
4. Insertion-style flowmeters shall be provided with all installation hardware necessary to enable installation and removal of flowmeters without system shutdown. No special tools shall be required for insertion or removal of the meter.
5. Inline-style flowmeters shall be installed with a bypass assembly and isolation valves to enable installation and removal of these flowmeters without system shutdown.
6. Dual turbine, vortex shedding, or magnetic flowmeter (per approved submittal).

7. *Magnetic Full Bore Meter (Preferred)*: Sensor shall be installed in a location clear from obstruction 5 pipe diameters upstream and 2 pipe diameters downstream, including pipe elbows, valves, and thermowells.
8. *Insertion Vortex Shedding Meter*: Sensor shall be installed in a location clear from obstruction 10 pipe diameters upstream and 5 pipe diameters downstream, including pipe elbows, valves, and thermowells.
9. *Dual Turbine Meter*: Flow sensing turbine rotors shall be non-metallic and not impaired by magnetic drag. Sensor shall be installed in a location clear from obstruction 10 pipe diameters upstream and 5 pipe diameters downstream, including pipe elbows, valves, and thermowells.
10. Verify that air vents or other air removal equipment exists in the system piping. If none exists, install appropriate air-removal equipment downstream of flowmeter.

B. Fluid Temperature Devices

1. Each temperature measurement device shall have a rated instrument accuracy within 0.1°F (0.056°C). Precision shall be within 0.1°F (0.056°C). Resolution of any signal conditioning and readout device shall be within 0.05°F (0.0278°C). These requirements include the sensor and any signal conditioning.
2. Temperature measurement devices, including any signal conditioning, shall be bath-calibrated (NIST traceable) for the specific temperature range for each application. Temperature measurement devices used in differential temperature measurement shall be matched and calibrated together by the manufacturer. The calculated differential temperature used in the energy calculation shall be accurate to within 2% of the difference (including the error from individual temperature sensors, sensor matching, signal conditioning, and calculations).
3. All piping immersion temperature sensors shall be inserted in newly installed brass or stainless steel wells that are located downstream of flowmeter placement and that allow for the removal of the sensor from the well for verifying calibration in the field. Allow for at least 2 pipe diameters upstream and 1 pipe diameter downstream clear of obstructions. The well shall penetrate the pipe a minimum of at least 2 in. (50 mm) and a maximum of up to half the pipe diameter. The use of direct immersion sensors is not acceptable.
4. All piping immersion temperature sensors shall be coated with heat or (thermal) paste prior to being inserted in the wells. The paste shall be rated and keep consistency over the expected temperature range. A thermal-conducting metal oxide, a dielectric silicon-based compound, is available with an operational range of -65°F to 400°F (-54°C to 205°C).

C. Btu Meters

1. The entire Btu measurement system shall be manufactured by a single manufacturer and shall consist

of a flowmeter, two solid-state temperature sensors, a Btu meter, thermowells, all required mechanical installation hardware, and color-coded interconnecting cable. The entire system shall be serialized and include NIST-traceable factory wet calibration of the complete system. All equipment shall be covered by a manufacturer's transferable two-year "No Fault" warranty.

2. The requirements in "A" and "B" above apply.
3. Each Btu meter shall provide a solid-state dry contact output for energy total and analog outputs (4–20 mA or 0–10 VDC) for thermal rate, liquid flow rate, supply temperature, and return temperature. As an alternative to the analog outputs, the Btu meter shall provide serial communications compatible with the data acquisition system. The interface meter to the data acquisition system shall provide access to all available data.
4. The analog thermal rate output and dry-contact energy output shall have a rated accuracy within $\pm 2\%$ of reading.
5. The maximum dry-contact energy increment shall be no more than 1/10,000 of full scale (1000 tons yields 0.1 ton-hours per pulse = 10,000 pulses per hour = 2.78 Hz).
6. The Btu meter electronics shall be housed in a steel $8 \times 10 \times 4$ in. NEMA-13 enclosure and shall include a front-panel-mounted two-line alphanumeric LCD display for local indication of thermal rate, liquid flow rate, and supply and return temperatures. A single 24 or 120 VAC connection to the Btu meter shall provide power to the meter electronics and to the flowmeter. Each Btu meter shall be factory programmed for its specific application and shall be re-programmable by the user using the front panel keypad (no special interface device or computer required). A certificate of calibration shall be provided with each Btu meter.

D. Power Measurement Devices

1. Power shall be measured using sensors and signal conditioning that yield true RMS power based on the measured current, voltage, and power factor. The power measurement device shall be capable of sensing direct digital control (DDC) and fundamental harmonics through the 33rd harmonic (odd and even).
2. Each power measurement device shall have a rated instrument accuracy within $\pm 1.5\%$ of the reading. Precision shall be within $\pm 1.0\%$ of the reading. Resolution of any signal conditioning and readout device shall be within $\pm 0.1\%$ of the reading. The instrument shall be capable of measuring power within the stated accuracy over the entire range of flow. These requirements include the sensor and any signal conditioning.
3. Single kW or Modbus output from VFD. **Note:** Older VFDs provide data that can be $\pm 10\%$.

E. Weather Station

1. Each temperature measurement device shall have a rated instrument accuracy within 0.2°F (0.1111°C). Precision shall be within 0.2°F (0.1111°C). Resolution of any signal conditioning and readout device shall be within 0.05°F (0.0278°C). These requirements include the sensor and any signal conditioning.
2. The weather station should be mounted on a north-facing wall. If solar exposure is possible, it shall be mounted in a ventilated enclosure that allows access by the operators for maintenance.
3. Maintenance shall include replenishment of distilled water in the reservoir and fresh wicks every six months. Provide a three-year supply of fresh wicks.

F. Wiring

1. All wiring shall be provided and installed as required to meet the measurement accuracy goals specified in Table E-1.
2. All control and interlock wiring shall comply with national and local electrical codes.
3. All NEC Class 1 (line voltage) wiring shall be UL Listed in approved raceway per NEC requirements.
4. All low-voltage wiring shall meet NEC Class 2 requirements. (Low-voltage power circuits shall be sub-fused when required to meet a Class 2 current-limit.) Class 2 wiring shall be installed in UL Listed approved raceways, except where wires are concealed in accessible locations. Approved cables not in raceways may be used, provided that the cables are UL Listed for the intended application. For example, cables used in ceiling return plenums shall be UL Listed specifically for that purpose.
5. Do not install Class 2 wiring in a raceway containing Class 1 wiring. Boxes and panels containing high-voltage wiring and equipment shall not be used for low-voltage wiring except for the purpose of interfacing the two (e.g., relays and transformers).
6. Do not install wiring in a raceway containing tubing.
7. Where Class 2 wiring is used without a raceway, it shall be supported from or anchored to structural members neatly tied at 10 ft (1 m) intervals. Cables shall not be supported by or anchored to ductwork, electrical raceways, piping, or ceiling suspension systems and shall be located at least 1 ft (300 mm) above ceiling tiles and light fixtures.
8. All wire-to-device connections shall be made at a terminal block or terminal strip. All wire-to-wire connections shall be made at a terminal block.
9. All field wiring shall be properly labeled at each end with self-laminating typed labels indicating device address for easy reference to the identification schematic. All power wiring shall be neatly labeled to indicate service, voltage, and breaker source.
10. Coded conductors with different colored conductors shall be used throughout.
11. All wiring within enclosures shall be neatly bundled and anchored to permit access and prevent restriction to devices and terminals.

12. Maximum allowable voltage for control wiring shall be 120 V. If only higher voltages are available, the Contractor shall provide step-down transformers.
13. All wiring shall be installed as continuous lengths, with no splices permitted between termination points.
14. Install plenum wiring in sleeves where it passes through walls and floors. Maintain fire rating at all penetrations.
15. Sizes of raceways and sizes and types of wire shall be the responsibility of the Contractor, in keeping with the manufacturer's recommendation and NEC requirements.
16. Include one pull string in each raceway that is 1 in. (25 mm) or larger.
17. Control and status relays shall be located in designated enclosures only. These enclosures include packaged equipment control panel enclosures unless they also contain Class 1 starters.
18. Conceal all raceways, except those within mechanical, electrical, or service rooms. Install raceway to maintain a minimum clearance of 6 in. (150 mm) from high-temperature equipment (e.g., steam pipes or flues).
19. Secure raceways with raceway clamps fastened to the structure and spaced according to code requirements. Raceways and pull boxes may not be hung on flexible duct strap or tie rods. Raceways shall not be run on or attached to ductwork.
20. Install insulated bushings on all raceway ends and openings to enclosures. Seal top end of all vertical raceways.
21. The installing Contractor shall terminate all control and/or interlock wiring and shall maintain updated (as-built) wiring diagrams with terminations identified at the job site.
22. Flexible metal raceways and liquid-tight, flexible metal raceways shall not exceed 3 ft (900 mm) in length and shall be supported at each end. Flexible metal raceway less than 0.5 in. (13 mm) electrical trade size shall not be used. In areas exposed to moisture, liquid-tight, flexible metal raceways shall be used.
23. Raceway shall be rigidly installed, adequately supported, properly reamed at both ends, and left clean and free of obstructions. Raceway sections shall be joined with couplings (per code). Terminations shall be made with fittings at boxes, and ends not terminating in boxes shall have bushings installed.
24. Electrical service to control panels and control devices shall be provided by isolated circuits, with no other loads attached to the circuit, and shall be clearly marked at its source. The location of the breaker shall be clearly identified in each panel served by it. If a spare breaker is not available within an electrical panel, the installing Contractor shall be responsible for providing any and all equipment and labor necessary to supply an isolated circuit. Controllers controlling only packaged air-

conditioning equipment may be powered directly from the packaged unit's control circuit.

G. Data Acquisition

1. The data acquisition system's analog-to-digital converter (A/D) shall have a rated instrument accuracy of 0.05% of full scale. Precision shall be within 0.025% of full scale. The minimum resolution shall be within 0.025% of full scale range and within one second for time.
2. It is recommended that the A/D be a factory-calibrated monolithic successive approximating A/D or a successive-approximation register (SAR) converter A/D to at least native 10 bit or better with a minimum drift of 30 ppm/°C (54 ppm/°F) and minimum resolution of 2.44 mV/bit. Eight-bit devices using software or algorithms to achieve 10-bit resolution are not acceptable. Twelve-bit resolution is preferable.
3. The data acquisition system, including its control network and field panels, shall be capable of collecting data at all points at a minimum sampling interval of one minute without measurably affecting control performance. Continuous sampling is preferred.
4. Analog inputs from pulse-output wattmeters shall use the smallest resolution possible.

H. Sensors, Meters, and Calculated Values for Performance Monitoring (see Table E-2)

- I. An Instrumentation Table shall be submitted containing the following information.
 1. Point name
 2. *Point Description*: Provide building designation, system type, equipment type, engineering units, and functionality; include a description of its physical location
 3. Expected range (upper and lower limit)
 4. *Instrumentation (if applicable)*: manufacturer, model number, range, accuracy specification
- J. Based on Table E-2, a Data Point Summary Table shall be submitted containing the following information.
 1. Point name
 2. *Point Description*: Provide building designation, system type, equipment type, engineering units, and functionality; include a description of its physical location
 3. *Type*:
 - a. AI: analog input or binary output
 - b. DI: digital or binary input
 - c. CBAI: communication bus, gateway, or interface analog input
 - d. CBDI communication bus, gateway, or interface digital (binary) input
 - e. P: programmed (e.g., soft point in control sequence such as a proportional-integral-derivative (PID) input or output)
 - f. C: calculated value
 4. Expected range (upper and lower limit)

TABLE E-2 Example Descriptions and Data for Sensors, Meters, and Calculated Values

#	Point Name	Point Description and Location if Applicable	Input Type	Sensor Type or Calculation Method	Required End-to-End Accuracy (Note 1)	Display Resolution	Refresh Interval (min)	Trend Interval (min)
5	Chlr1 kW	Chiller 1 Power	AI	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter; use maximum resolution if pulse output	±1.5%	0.01 kW	1	1
6	Chlr2 kW	Chiller 2 Power	AI	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter; use maximum resolution if pulse output	±1.5%	0.01 kW	1	1
9	SecChW/P1 kW	Secondary Chilled-Water Pump 1 Power from VFD	AI	Reprogram existing VFD analog output for kW	±3.0%	0.01 kW	1	1
10	SecChW/P2 kW	Secondary Chilled-Water Pump 2 Power from VFD	AI	Reprogram existing VFD analog output for kW	±3.0%	0.01 kW	1	1
11	Chlr1CWP kW	Chiller 1 CW Pump Power	AI	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter; use maximum resolution if pulse output	±1.5%	0.01 kW	1	1
12	Chlr2CWP kW	Chiller 2 CW Pump Power	AI	True RMS, three-phase, integrated equipment, stand-alone analog output or networked power meter; use maximum resolution if pulse output	±1.5%	0.01 kW	1	1
24	ClgTF1 kW	Cooling Tower Fan 1 Power	AI	Reprogram existing VFD analog output for kW	±3.0%	0.01 kW	1	1
25	ClgTF2 kW	Cooling Tower Fan 2 Power	AI	Reprogram existing VFD analog output for kW	± 3.0%	0.01 kW	1	1
26	Chlr1ChW Flow	Chiller 1 CHW Flow	AI	Hot tapped insertion vortex shedding	±2.0%	0.1 gpm	1	1
27	Chlr2ChW Flow	Chiller 2 CHW Flow	AI	Hot tapped insertion vortex shedding	±2.0%	0.1 gpm	1	1
32	Chlr1ChWS Temp	Chiller 1 CHWS Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1
33	Chlr1ChWR Temp	Chiller 1 CHWR Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1
34	Chlr1CWS Temp	Chiller 1 CWS Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1
35	Chlr1CWR Temp	Chiller 1 CWR Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1
36	Chlr2ChWS Temp	Chiller 2 CHWS Temperature	AI	1000 ohm thermistor or RTD	± 0.1°F	±0.01°F	1	1
37	Chlr2ChWR Temp	Chiller 2 CHWR Temperature	AI	1000 ohm thermistor or RTD	± 0.1°F	±0.01°F	1	1
38	Chlr2CWS Temp	Chiller 2 CWS Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1
39	Chlr2CWR Temp	Chiller 2 CWR Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1

* Notes:
1. Percentage refers to % of reading unless otherwise noted.
2. Contractor shall develop constants used in calculations except as noted.
C4 = 0.0417, which assumes chilled water at 45°F (7.2°C), no glycol.
* AI = analog input; C = calculated value

TABLE E-2 Example Descriptions and Data for Sensors, Meters, and Calculated Values (continued)

#	Point Name	Point Description and Location if Applicable	Input Type	Sensor Type or Calculation Method	Required End-to-End Accuracy (Note 1)	Display Resolution	Refresh Interval (min)	Trend Interval (min)
40	Chlr ChWInHdr Temp	Chiller CHW Inlet Header Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1
41	Chlr CWInHdr Temp	Chiller CW Header Temperature	AI	1000 ohm thermistor or RTD	±0.1°F	±0.01°F	1	1
42	OA Temp	Ambient Dry-Bulb Temperature	AI	In weather station in fully shaded location or ventilated enclosure	±0.2°F	±0.01°F	1	10
43	OAWb Temp	Ambient Wet-Bulb Temperature	AI	In weather station in fully shaded location or ventilated enclosure	±0.2°F	±0.01°F	1	10
49	Chlr # ChWp kW	Chiller # Chilled-Water Pump Amps converted to kW	C	Measured value [#7; #8] multiplied by a constant #C2	N/A	0.1 kW	1	10
50	Chlr # CWP kW	Chiller # Chilled-Water Pump Amps converted to kW	C	Measured value [#11; #12] multiplied by a constant #C3	N/A	0.1 kW	1	10
51	Chlr # tons	Chiller # Thermal Cooling Output	C	(Difference of 2 measured values) [#34, #33; #37, #36] multiplied by measured value [#26; #27] multiplied by a constant #C4	N/A	0.1 tons	1	10
52	Chlr # kW/ton	Chiller # Efficiency	C	Measured value [#5; #6] divided by measured value [#51a; #51b]	N/A	0.01 kW/ton	1	10
53	ChW Plant tons	Chilled-Water Plant Thermal Cooling Output	C	Sum of measured values [#51a, #51b]	N/A	0.1 tons	1	10
54	ChW Plant kW/ton	Chilled-Water Plant Efficiency	C	(Sum of measured values) [#5, #6, #49a, #49b, #9, #10, #50a, #51b, #24, #25] divided by calculated value [#53]	N/A	0.01 kW/ton	1	10
55	Avg ChW Plant tons	Average Chilled-Water Plant Thermal Cooling Output	C	30 minute running average of calculated value [#53]	N/A	0.1 tons	1	10
56	Max ChW Plant tons	Maximum Averaged Chilled-Water Plant Thermal Cooling Output	C	Maximum 30 minute running average of a calculated value [#55]	N/A	0.1 tons	1	10
57	Daily ChW Plant Tons-hrs	Daily Chilled-Water Plant Thermal Cooling Energy	C	Calculated value [#53] integrated over 24 h period	N/A	0.1 ton-hrs	1	10
58	Max Daily ChW Plant Tons-hrs	Maximum Daily Chilled-Water Plant Thermal Cooling Energy	C	Maximum 24 h total of a calculated value [#57]	N/A	0.1 ton-hrs	1	10
72	Avg ChW Plant Eff	Average Chilled-Water Plant Efficiency	C	30 minute running average of calculated value [#54]	N/A	0.01 kW/ton	1	10

Notes:

- Percentage refers to % of reading unless otherwise noted.
- Contractor shall develop constants used in calculations except as noted.
C4 = 0.0417, which assumes chilled water at 45°F (7.2°C), no glycol.
* AI = analog input; C = calculated value

5. Input resolution (this is critical for pulse type watt-meters; use the smallest resolution possible)
 6. Data-trend interval
 7. Number of samples stored in local controller before transfer to database
 8. *Communication Protocol Information*: Ethernet backbone network number, device ID, object ID
 9. Block-trend grouping designation
 10. Energy management control system (EMCS) controller designation
- K. Logic diagrams and/or code and any constants for creating the calculated values specified in Table E-2 shall be submitted for review and approval.

V. Data Point Naming Convention

- A. Name Architecture
 1. Format is a four-element string including location, system, equipment, and function.
 2. Each element in a string shall be as long as possible to aid readability without exceeding the overall maximum string length.
 3. Location shall include building, floor, and room where applicable.
- B. Naming Rules
 1. Names shall be unique. Each of the four elements in a name should include a number if required for uniqueness.
 2. Use agreed-upon names if possible. If for some reason a name is too long, an abbreviated string should include a capitalized first letter of each element or other delimiter as appropriate (e.g., a period). Be as clear as possible, using as much of the original name as possible. Do not omit a word or first letter.
 3. When using uppercase letters as delimiters, do not use uppercase other than for the first letter of an element word. Do not use the same capitalized letter for different meanings, except for an existing site-specific designation. See examples in abbreviations below.
- C. Abbreviations
 - a. BACnet-defined abbreviations shall be used if possible, or use abbreviations shown in Table E-3.

VI. Trending

- A. If not already required, provide the following trends.
 1. All specified analog and digital input and output values.
 2. All set points.
 3. All PID loop input and output values.
 4. All calculated values.
 5. Change of value (COV) sampling may only be used for digital input and output values.
- B. Group trend values in trend blocks in a logical way. See Section VII for additional requirements. Identify trend blocks in the Data Point Summary Table.
 1. Group all control loop values together. An example would be an air-handling unit discharge air temperature with the analog temperature input, output(s) to

TABLE E-3 Data Point Naming Abbreviations

AH	= Air Handler	L	= Leaving
Blr	= Boiler	Ltg	= Lighting
Bldg	= Building	Mn	= Main
Chlr	= Chiller	OA	= OutdoorAmbient
ChW	= Chilled Water	P	= Pump
Clg	= Cooling	R	= Return
CW	= Condenser Water	Rm	= Room
DPr	= Differential Pressure	S	= Supply
E	= Entering	Sec	= Secondary
Eff	= Efficiency	Stat	= Status
EUI	= Energy Use Intensity	Sys	= System
F	= Fan	T	= Tower
Flr	= Floor	Temp	= Temperature
InHdr	= Inlet Header	Tot	= Total
GPr	= Gauge Pressure	Wb	= Wet-bulb
He	= Heat or Heating	Z	= Zone
Ho	= Hot		

the control device(s), and PID control setpoint on the same trend.

2. Group all data for one “system” together. An example would be chilled-water data that groups chiller status, chilled-water supply temperature, chilled-water return temperature, chilled-water supply setpoint temperature, and outside air temperature together.

- C. See Section VIII for other requirements.

VII. Data Archival

- A. Trend Data Storage
 1. The system, including the control network and field panels, shall be capable of collecting and storing all point data at a uniform sampling interval of one minute without measurably affecting control performance.
 2. Trend data shall be archived in a database in time intervals no less frequently than once per day.
 3. The database shall allow applications to access the data while the database is running. The database shall not require shutting down in order to provide read-write access to the data. Data shall be able to be read from the database without interrupting the continuous storage of trend data being carried by the EMCS.
 4. Data shall be stored in MS-Access or structured query language (SQL) compliant database format and shall be available through the Owner’s intranet and/or internet (with appropriate security clearance).
 5. All data shall be stored in database file format for direct use by third-party programs. Operation of the system shall stay completely online during all graphing operations.

- B. The system server shall be capable of periodically gathering performance data stored in the field equipment and automatically archiving these data without operator intervention. All performance data required to generate the graphic displays listed in Section VIII shall be archived. Archive files shall be appended with new data, allowing data to be accumulated. Systems that write over archived data shall not be allowed unless limited file size is specified and automatic archiving is employed on a scheduled basis to prevent loss of data. Display all performance data in standard engineering units.
- C. Trend Data Export for Analysis by Other Software
 1. Historical and current data held in temporary memory must be exportable as specified by the owner to one or more formats for analysis by external software. Examples include:
 - a. Text (Comma or tab delimited with “ ” text delimiters)
 - b. MS Excel
 - c. MS Access
 - d. dBase
 - e. SQL
 2. Exported data shall have the following characteristics:
 - a. There shall be no duplicate records. Each time/date stamp for a specific point shall be unique.
 - b. The data shall be fully contained in a single file or table for each point. Data shall not span multiple files or database tables.
 - c. Each field of data shall have one and only one unique identifier. The label shall be in the first row of the file. Labels should not be repeated in the stream of data.
 - d. Each table or file shall have a single date/time stamp. Multiple fields that are sampled on the same time stamp can be combined in a single file or table provided that they have the same number of records and are stored in the following format:

Date/Time	Field 1	Field 2	...	Field n
DateTimeValue1	Value 11	Value 21	...	Value n1
...				
DateTimeValuej	Value 1j	Value 2j	...	Value nj
 - e. Date/Time fields shall be in a single column in a format automatically recognized by MS Access or MS Excel.
 3. Data transfer shall be accomplished by open database connective (ODBC) or Web services.
- D. Operators shall be able to change the performance monitoring setup. This includes the meters to be logged, meter pulse value, and the type of energy units to be logged. All points on the system shall be capable of being displayed, archived, and re-displayed from archive.

g. Provide indication of whether VFD is in “Auto”

- E. Archiving program shall follow password levels requirements for users to delete, modify, or change archive parameters.

VIII. Graphics Requirements

- A. The DDC system shall (1) show on the building operator's computer all of the graphics listed in this section and (2) perform necessary calculations to produce the output graphic reports listed.
 1. See below for specific requirements for each graphic type.
 2. Sensor locations shall be identified on all graphics where appropriate.
 3. Each graphic shall match the actual configuration of the unit or system such that an operator can visit the unit and visually be able to identify ductwork and devices from a screen print of the graphic. A generic flow schematic will not be acceptable.
- B. Outdoor Air Conditions
 1. Provide a graphic presenting data as shown in Figure E-1.
 2. Provide active text links for
 - a. Site
 - b. Building
 - c. Floors
 - d. Major systems
 - e. Summary tables
- C. Performance Monitoring Summary Table—Facility Chilled-Water System
 1. Provide summary information from each performance monitoring graphic.
 2. This graphic shall provide text links to each performance graphic:
 - a. Site Weather
 - b. Chiller Plant Performance Monitoring (Summary Table)
 - (1) Chilled-Water Plant Efficiency (kW/ton)
 - (2) Average Chilled-Water Plant Thermal Cooling Output (tons)
 - (3) Maximum Average Chilled-Water Plant Thermal Cooling Output (tons)
 - (4) Daily Chilled-Water Plant Thermal Cooling Energy (ton-hrs)
 - (5) Maximum Daily Chilled-Water Plant Thermal Cooling Energy (ton-hrs)
 - (6) Chiller Efficiency, Chiller #n (kW/ton)
- D. Chilled-Water (ChW) Plant
 1. This equipment graphic shall display:
 - a. Chiller(s)
 - b. Cooling tower(s)
 - c. Pumps
 - d. Valves
 - e. Sensors
 - f. Related status and performance data, including OAT, OARH, Site Power, Building Cooling Load (tons), ChW Plant Power, Chiller kW/ton or “Hand” mode.

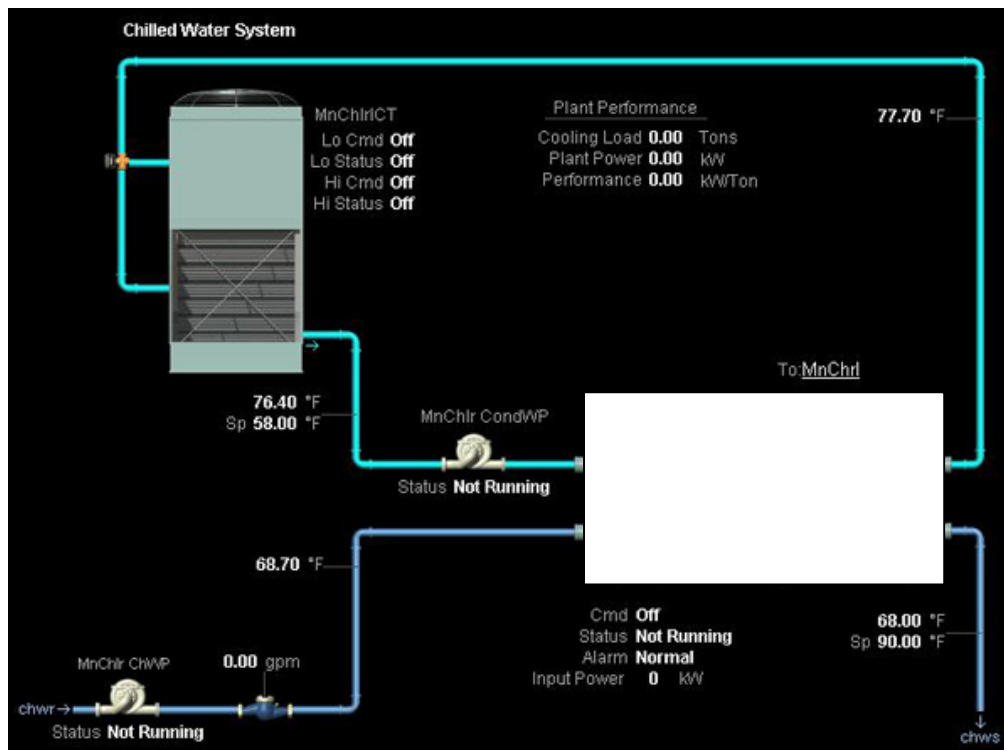


Figure E-1 Example chilled-water plant graphic.

2. This graphic shall also display text links to:
 - a. Site
 - b. Chiller #
 - c. ChW Plant Performance
 - d. AH# Table
3. Figure 8.D.1 shows an example diagram of a chilled-water plant with status displays of key components.
- E. Chilled-Water Plant Performance Monitor
 1. This performance visualization graphic is a “child” of the ChW Plant equipment graphic.
 2. This performance visualization graphic shall display:
 - a. Current and historical plant kW/ton data
 - b. Current trend graph
 3. This graphic shall also display active text links to:
 - a. Site
 - b. Chiller Performance
 - c. ChW Plant
 4. This graphic includes a grouping of four time-series charts for “Chlr Tons”, “Chlr Power + ChW plant Power”, “ChW plant Efficiency (in kW/ton)”, and “OA Temp”
- F. Chilled-Water Plant Performance Modes
 1. Like “ChW Plant Performance Monitor” described above, this performance visualization graphic is a “child” of the ChW Plant equipment graphic.
 2. This performance visualization graphic shall display:
 - a. Current and historical plant mode data
 3. This graphic shall also display active text links to:
 - a. Site
 - b. Chiller Performance
 - c. ChW Plant
- G. (mfg) Chiller #
 1. This equipment graphic shall display the chiller data indicated in Figure 1.
 2. This graphic shall also display text links to:
 - a. Site
 - b. Chiller# Performance
 - c. ChW Plant
 - d. ChW Plant Performance
- H. Chiller # Efficiency (kW/ton)
 1. This Performance Metric graphic is a “child” of the (mfg) Chiller # equipment graphic.
 2. This Performance Metric graphic shall display:
 - a. Current and historical chiller kW/ton data
 - b. Current trend graph
 3. This Performance Metric graphic requires the following performance metrics and data points (1) Chiller Power (kW) and (2) Chilled-Water Output (tons). For more detail, see Section IV above.
 4. This graphic shall also display active text links to:
 - a. Site
 - b. (mfg) Chiller #
 - c. ChW Plant
 - d. ChW Plant Performance
 - e. Performance-Metric Summary Graphic
- I. ChWP# VFD

1. This equipment graphic shall display the ChWP and data.
 2. This graphic shall also display text links to:
 - a. Site
 - b. Chiller# Performance
 - c. ChW Plant
 - d. ChW Plant Performance
- J. ChWP# VFD Performance Monitor
1. This performance graphic shall display the ChWP VFD performance, as indicated in Figure 1.
 2. This graphic shall also display text links to:
 - a. Building
 - b. ChW Plant
 - c. ChW Plant Performance

IX. Commissioning

- A. Contractor shall provide Submittals as specified in Section XI. They are to be reviewed and approved by the Owner's representative prior to hardware and software installation and programming.
- B. *Installation and Setup:* For hardware and each software element, the Contractor shall conduct checks and functional tests as necessary to verify that the correct hardware and software have been installed as specified and work properly per this specification.
1. *Sensors:* Inspect the installation of all sensors. Verify that all sensors as specified in Section IV have been installed according to the manufacturer's installation requirements, that they are located according to the contract documents, and that calibration has been checked according to Section B.
 2. *Monitored Points Setup:* Verify that the required monitoring points as specified in Sections III, IV, and VI have been programmed, including pseudo and calculated points required for performance monitoring and preventative maintenance. Verify that all performance metrics and data points are viewable in the appropriate graphics screen.
 3. *Trend Setup:* Assure that each element of Section VI is functional and reliable.
 4. *Archival Database:* Assure that each element of Section VII is functional and reliable. Determine whether the data are being sampled at the proper time intervals required and if, how, and where the data is being archived. Determine whether the appropriate functionality has been provided. Assure that tools are available to access and view archived data.
 5. *Visualization and Reporting Software Installation and Setup:* Assure that each element of Section VIII is functional and reliable.
 6. Assure that backup copies of software are available for restoring the system to its original functional setup.
- C. *Sensor Calibration Verification Requirements:* Test equipment used for testing calibration of field devices shall be at least twice as accurate as respective field

devices. The following provides general requirements for verifying DDC sensor calibration in the field.

1. *Temperature:* Use a multipoint verification check at various points in the operating range (including minimum, typical, and maximum) utilizing a calibrated thermometer and Dewar flask or a calibrated portable drywell temperature probe calibrator and compare it to the I/O point data at a user interface to field-verify the through-system measurement tolerance.
2. *Relative Humidity:* Use a single-point calibrator or portable environmental chamber that has been lab calibrated with a NIST traceable dew-point monitor and compare it to the I/O point data at a user interface to field-verify the through-system measurement tolerance. Salt baths are not recommended outside of the laboratory—they do not transport well and their accuracy is greatly affected by the unstable environmental conditions usually found in the field.
3. *Fluid Flow:* Use a portable ultrasonic flowmeter (UFM) to spot-check flow(s) and compare the flow(s) to the I/O point data at a user interface to field-verify the through-system measurement tolerance. One must be aware that UFM's are velocity-dependent devices and are highly vulnerable to variations in flow profile and installation error. They should be considered 5% devices for pipe diameters 12 in. and under. UFM flow-profile compensation assumes a fully developed flow profile at the calculated Reynolds number. Even at 10 diameters downstream of an elbow, a significantly altered flow profile will occur. It is suggested that flow profile compensation be turned off and the acceptable deviation between the measuring flowmeter and the UFM be restricted to 5% for applications with less than 10 pipe diameters of straight length pipe upstream of the UFM. If variable flow conditions exist, both the flow and the flow profile will need to be evaluated at a range of conditions. See *ANSI/ASHRAE Standard 150, Method of Testing the Performance of Cool Storage Systems*, Annex D, for a detailed method.

D. Demonstration/Witness Tests

1. The Contractor shall demonstrate to the satisfaction of the Owner that these specifications have been fully implemented. The Contractor shall provide those services necessary to support witness testing.
2. These checks and tests are not intended to replace the Contractor's normal and accepted procedures for installing and pre-testing equipment or to relieve the Contractor of the standard checkout and start-up responsibilities but to assure the Owner that design intent has been met. Any equipment, condition, or software program found not to be in compliance with the acceptance criteria shall be repaired or corrected and then retested until satisfactory results are obtained.

3. Actual checks and tests will be selected by the Owner after the Contractor has verified that the installation is complete and operational. The following checks and tests are recommended.
 - a. Verify that all points have been provided and are in the proper location as specified.
 - b. Verify the proper use of point naming convention.
 - c. Verify the programming of calculated values.
 - d. Verify the proper implementation of graphic requirements.
 - e. Field-verify the calibration of a sample of measured points.
- E. Actual checks and tests will be selected by the Owner after the Contractor has verified that the installation is complete and operational. The following checks and tests are recommended.
 1. Verify that all points have been provided as specified.
 2. Verify the proper use of point-naming convention.
 3. Verify the programming of calculated values.
 4. Verify the proper implementation of graphic requirements.
 5. Field-verify the calibration of a sample of measured points.
 6. Conduct a 90-day data-loss test. Verify that 99% of data is archived.
- F. These checks and tests are not intended to replace the Contractor's normal and accepted procedures for installing and pre-testing equipment or relieve the Contractor of the standard checkout and start-up responsibilities but to assure the Owner that design intent has been met. Any equipment, condition, or software program found not to be in compliance with the acceptance criteria shall be repaired or corrected and then retested until satisfactory results are obtained.

X. Training

- A. Hands-on on-site training shall be provided to in-house operating staff. Training shall include a conceptual overview of the purpose of the performance monitoring system, its relationship to the complete building control system, and its overall use, as well as the following detailed aspects of the performance monitoring system.
 1. Instrumentation
 2. Data Communications
 3. Performance-Metrics Calculations and Data Points
 4. Data Archival Software and Procedures
 5. *Data Visualization Software Use*: Training shall enable operating personnel to understand the following:
 - a. Proper use of the graphic displays for tracking building performance.
 - b. How to use each performance-monitoring graphic to diagnose the proper and improper operation and performance of the subject equipment.

- c. What sets of remedial actions might be indicated when given out-of-range values for each performance-monitoring graphic.
- B. Assure that in-house staff is familiar with all submittals listed in Section XI and knows their storage locations.

XI. Submittals

- A. Submittals Review Process
 1. Each submittal package shall be complete; partial submittals will not be accepted unless Owner's representative agrees to an alternative submittal schedule.
 2. Submit two (2) of each submittal package to Owner's representative for review.
 3. The Owner's representative will return one copy with corrections noted.
 4. The Contractor shall make corrections and resubmit four (4) clean copies of submittals for final approval. If all corrections have not been made and further resubmittal is required, the Contractor will reimburse Owner's representative for additional review time at normal billing rates.
- B. *Construction Documents*: The Contractor shall submit the following documents for review and approval by the Owner's representative.
 1. *Instrumentation*: A complete Instrumentation submittal, as specified in Section IV, shall be provided for approval prior to purchasing and installing any instrumentation. Any instrumentation purchased or installed prior to approval is subject to rejection or revision.
 2. *Data-Point Summary Table*: A complete Data-Point Summary Table submittal, as specified in Section IV, shall be provided for approval prior to its implementation. Any installation or programming generated prior to approval is subject to rejection or revision.
 3. *Calculation Logic Diagrams*: A complete Calculation Logic Diagram submittal, as specified in Section IV, shall be provided for approval prior to any programming. Any programs generated prior to approval are subject to rejection or revision.
 4. *Data Archive Procedure*: A complete Data Archive Procedure submittal, as specified in Section VII, shall be provided for approval prior to its implementation. Any procedure generated prior to approval is subject to rejection or revision.
 5. *Block-Trend Groupings*: A complete Block-Trend Grouping submittal, as specified in Section VI, shall be provided for approval prior to any programming. Any graphics generated prior to approval are subject to rejection or revision.
 6. *Graphic Diagrams*: A complete Graphic Diagram submittal, as specified in Section VII, shall be provided for approval prior to any graphics generation. Any graphics generated prior to approval are subject to rejection or revision.
- C. Contractor Quality Assurance Documents

1. The Contractor shall prepare forms for documenting that all required hardware and software has been installed and calibrated and are operating properly and submit the forms for approval. The forms shall be tabular and include the following:
 - a. Checks, tests, and simulations to be performed
 - b. Expected outcomes
 - c. Actual outcome
 - d. Indication of pass or fail
 - e. A space above or below for the party performing the activity to sign and indicate the actual date of the activity
 2. The Contractor shall submit documentation on approved forms that all required hardware and software have been installed and calibrated and are operating properly prior to the commencement of the activity.
- D. Training Documents
1. The Contractor shall prepare training materials in both hard copy and electronic form and submit for approval. Training materials shall include, but not be limited, to the following:
 - a. Project description
 - b. Facility description

- c. Hardware, software, and other sensor and materials training guides
- d. *Performance Monitoring System*: A complete description of the system and its use, including a discussion of related adjustments, scheduling, sequences, trending, alarms, and approved construction document products as applicable.

BIBLIOGRAPHY FOR APPENDIX E

- E-1 Material for this appendix is based on information from a CEC PIER project that developed *A Specification Guide for Performance Monitoring Systems*. The current draft for this specification guide can be found at <http://cbs.lbl.gov/performance-monitoring/specifications/>.
- E-2 Gillespie, Kenneth, et al. *A Guide for Specifying Performance Monitoring Systems in Commercial and Industrial Buildings*, National Conference on Building Commissioning, San Francisco, 2006.
- E-3 Gillespie, Kenneth, et al. Performance monitoring in commercial and institutional buildings. *HPAC Engineering* 78(12), December 2006.
- E-4 *ANSI/ASHRAE Standard 150-2000 (RA 2004), Method of Testing the Performance of Cool Storage Systems*, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, 2004.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX F— EXAMPLE APPLICATION

F1. INTRODUCTION

The intent of this appendix is to provide the users of this guideline with an example case that illustrates some of the issues they might need to address as part of the effort to gather, analyze, and use chilled-water plant data to improve performance.

The material for this example is taken from two papers: “Performance of a Hotel Chilled-Water Plant with Cool Storage” by Ken Gillespie, Steven Blanc, and Steve Parker^{F-1} and “Determining the Performance of a Chilled-Water Plant” by Ken Gillespie.^{F-2}

F2. BACKGROUND

Instrumentation was installed at a large facility to monitor the performance of its chilled-water system. The instrumentation was used to evaluate the effectiveness of electricity-price-based controls that automate response to real-time pricing (RTP) effects of enhanced scheduling and to characterize the operation and performance of the chilled-water plant, which included a newly installed cool storage system. The facility operates under real-time electricity rates. These capabilities were incorporated into a new building automation system (BAS), which also provides the performance monitoring and data management.

The chilled-water system included two large centrifugal chillers, a paralleled cool storage system with a centrifugal chiller and cool storage tanks isolated by a heat exchanger, twin cooling towers, and related pumps and controls. Fundamental to system performance optimization is the measurement of the individual temperatures, flows, and power that comprise the complete system. This project employed a results-oriented uncertainty analysis to select accurate instrumentation customarily used in the HVAC industry, used proper installation and advanced field calibration techniques, and validated measured data using redundant sensors and various energy and flow balances to monitor performance.

The data gathered included electricity use for all chillers, secondary coolant, chilled water, and condenser pumps, and the cooling tower fans. Thermal flow data was also collected for the storage system, ice chiller, direct cooling chillers, and chilled-water load loops.

F3. FACILITY DESCRIPTION

The facility has a measured peak electric load of 3764 kW and a design cooling load of 920 tons (3235 kW). The facility began operating under RTP.

F4. PLANT

The main chilled-water plant consists of:

- two 900 ton (3165 kW) chillers, each with dual centrifugal compressors,
- two 850 ton (2990 kW) open cooling towers, each dedicated to a chiller, and
- 555 hp (414 kW) in main pumps, including three paralleled chilled-water pumps and three paralleled condenser water pumps. One each of the chilled-water and condenser water pumps provided redundancy.

The facility air handling consists of:

- 90 hp (67 kW) in fans, currently operating with asynchronous drives (ASDs),
- variable-air-volume (VAV) systems for conference and meeting facilities, and
- a four-pipe fan-coil system for guest rooms.

The cool storage system (CSS) includes:

- a 450 ton (1583 kW) heat exchanger,
- a 160 ton (563 kW) direct expansion (DX) chiller providing 110 tons (387 kW) in ice-making mode,
- six 500 ton-hr (1758 kW-h) nominally rated internal melt ice-on-coil storage tanks,
- a 15 hp (11kW) secondary coolant pump with ASD, and
- automatic control valves and the chiller manufacturer's controller.

F5. PERFORMANCE MEASUREMENT OBJECTIVES

Performance measurement objectives include:

- Thermal Energy Storage (TES) and Building Systems Monitoring,
- Chilled-Water Plant Optimization, and
- Building Systems Optimization.

TES monitoring is used to determine the operational efficiency of the thermal storage system. Building systems monitoring is used to acquire operating data to facilitate the development of future control algorithms. Chilled-water plant optimal control is used to provide optimal control of the plant and includes the new TES system to maximize RTP cost savings. Sufficient and accurate data needed to be gathered. Based upon these needs, the monitoring system was designed to determine:

- CSS Electric Demand Profile and kWh/ton-hr delivered
- CSS Cooling Load Profile (tons)
- CSS Electric Demand, Energy Used, kWh/ton-hr delivered
- CSS Cooling Load Profile (tons)
- Cool Storage Tank State of Charge (ton-hrs)
- Existing Chillers Electric Demand, Energy Used, kWh/ton-hr delivered
- Existing Chillers Cooling Load Profiles (tons)
- Chilled-Water Plant Electric Demand, Energy Used, kWh/ton-hr delivered

The Main Cooling Plant

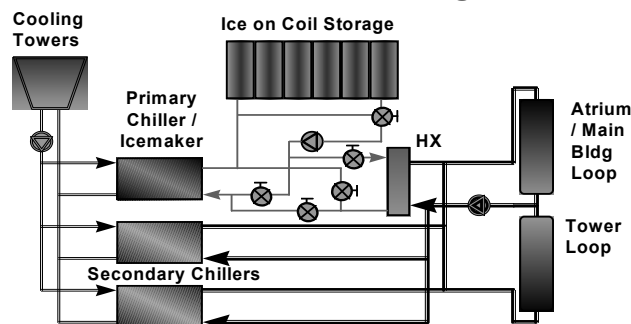


Figure F-1 Chilled-water plant flow diagram.

- Building Cooling Load Profile (tons)
- Building Electric Demand Profile and Energy Used
- Cool Storage Loop Heat Balance (for reset and error checking)
- Chilled-Water System Operating Modes (for mode efficiencies and capacity calculation)
- Building Cooling Loop Heat Balance (for reset and error checking)
- Building Electric Demand Profile and Energy Used
- Ambient Weather Conditions

Figure F-1 shows the basic plant configuration. The smaller chiller operates either to charge the ice storage system or to cool the main loop directly during periods of low load (winter). When either of the large chillers operates, it is usually at part-load.

F6. MONITORING OBJECTIVES AND REQUIREMENTS

The objective of the monitoring is threefold:

1. Data is to be used to facilitate development of control strategies and algorithms that provide near-optimal chilled-water control, including control of the new cool storage system.
2. Data is to be used to evaluate the effectiveness of the electricity-price-based controls that automate response to RTP.
3. The monitoring system is intended to measure the operational efficiency and capacities of the CSS, the two 900-ton chillers, the chilled-water plant as a whole, and facility cooling load.

The results presented here focus on the third objective.

General monitoring requirements are defined as follows:

- monitor all relevant chilled-water plant temperatures, flows and parasitic electric loads,
- employ sensors customarily found in the HVAC environment in order to constrain costs, and
- achieve an uncertainty in the results no greater than $\pm 5\%$ COP.

A thorough uncertainty analysis was performed in order to translate the desired maximum uncertainty in the final results into accuracy requirements for the individual measurements. The result gave specific measurement requirements as follows:

- $\pm 3.0\%$ of reading for in-situ flow measurements
- $\pm 0.1^\circ\text{F}$ ($\pm 0.05^\circ\text{C}$) for in-situ temperature measurements

The following points are monitored:

- 7 flows, including 2 cooling load loops, CSS primary and secondary, 2 cooling towers, and common cooling load return, which was added later
- 19 temperatures in the main plant and outside air temperature and relative humidity
- 10 unit electric demands
- 4 building electric utility kWh meters
- 4 CSS modes of operation
- 6 CSS tank storage-capacity points

F7. DATA ACQUISITION

Two standard recorders were used that provide 8 channels of digital, 8 channels of analog, and 8 channels of single-phase power measurement inputs plus remote on-line monitoring of data parameters. One unit provides 16 channels of digital, 15 channels of analog, and 16 channels of single-phase power measurement inputs plus remote on-line monitoring of data parameters. Averaged data was archived on a 15-minute basis. The loggers are linked internally in the building and accessed via a modem on an external phone line.

F8. SENSOR SELECTION

Project criteria established the prerequisite that the highest accuracy possible at reasonable cost be obtained by utilizing instrumentation customarily found in the HVAC environment. A goal of a maximum 5% COP uncertainty in the result was established. Sensors are required to monitor electric demand (chillers, pumps, tower fans, and main meters), fluid flow (secondary coolant, chilled water, and condenser water), fluid temperature, outside ambient temperature, outside ambient percent relative humidity, and CSS modes.

An initial uncertainty analysis was conducted for CSS efficiency and storage capacity on a typical data set to establish individual parameter requirements. The analysis yielded uncertainty requirements more stringent than that found in typical HVAC installations. The following uncertainties were established as goals for each measurement: water density, 0.1% of reading; volumetric flow rate, 3% of reading; water specific heat, 0.1% of reading; supply water temperature, return water temperature, and differential temperature, 0.1°F . Typical data in the ice-making mode at a design load of 110 tons yielded an uncertainty of 4.4% COP. The actual uncertainty of the result depended upon the magnitudes of the measured data.

In order to achieve these goals, special attention was placed on enhanced specifications during purchasing. Rigorous factory calibrations were required for both flow and temperature sensors. Flowmeters were factory calibrated with

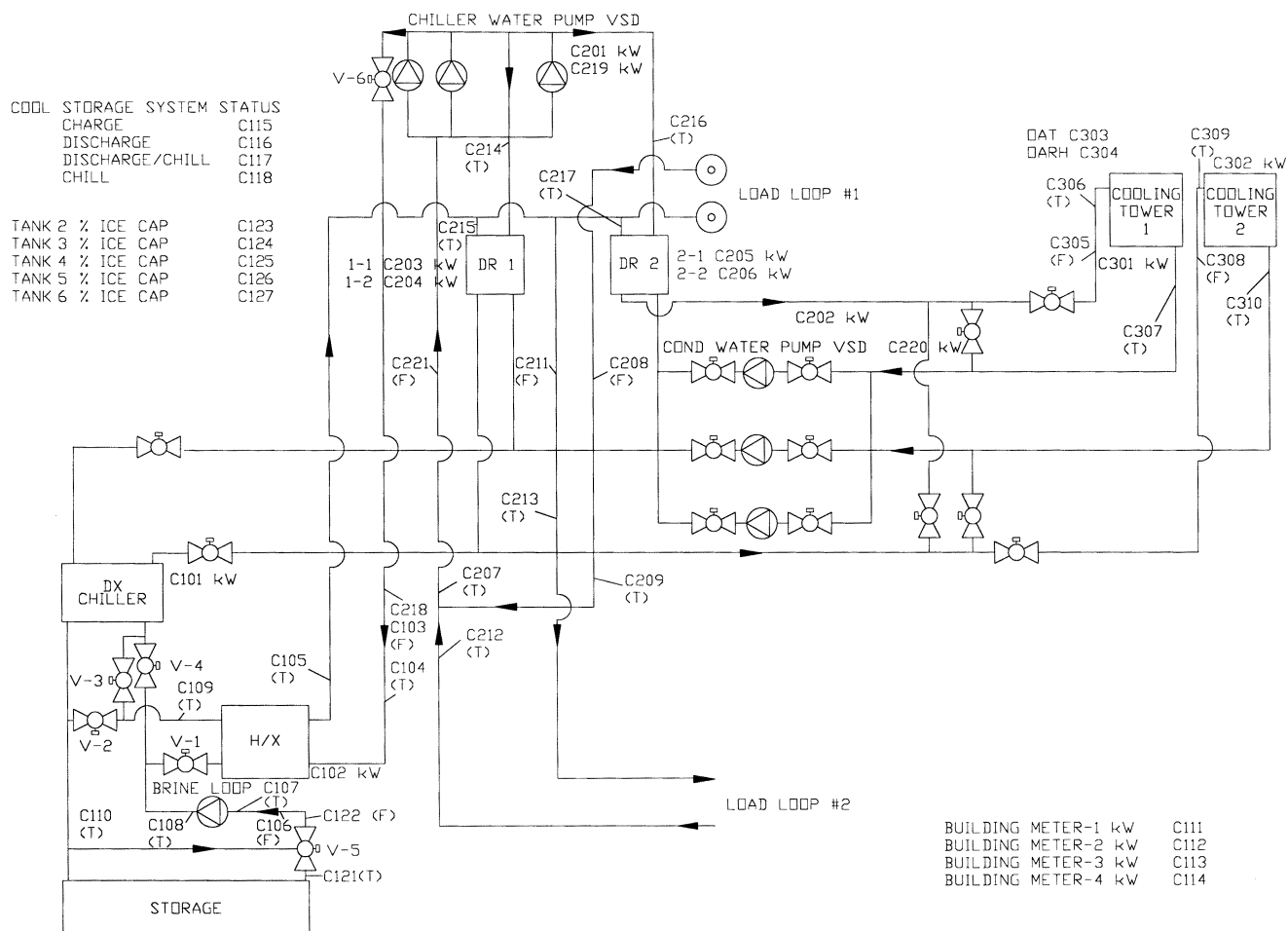


Figure F-2 Chilled-water plant schematic.

NIST-traceable equipment at the minimum, typical, and maximum expected flows for their respective ranges. Temperature sensors utilized in the cool storage, centrifugal chiller, and cooling tower subsystems were required to be factory matched for each system's range.

F9. DATA RELIABILITY

Special focus was placed on providing a proper measurement environment for each sensor. During the design of the CSS, specific installation specifications were prepared detailing installation locations and the required unobstructed straight lengths of pipe. Thermowells were provided for each temperature sensor. Because the existing piping for one cooling load loop did not allow sufficient straight lengths of pipe, a major section of 12 in. piping was rerouted to provide 36 ft of unobstructed run for the flow measurement. Where critical measurements occurred, redundant sensors were considered. All process heat exchangers were monitored sufficiently to allow local flow and heat balances and a system heat balance to facilitate error checking.

F10. PARAMETER LIST

The parameters in the following lists were either monitored or calculated in the logger or later in an analysis spread-

sheet. Monitored parameters are identified with channel numbers (C###) that can be used to identify their location in Figure F-2. HE is an abbreviation for *heat exchanger*; CT is an abbreviation for *current transformer*.

1. C101, Cool Storage Chiller Electric Demand, kW; split core 400A CTs.
2. C102, CSS Pump Electric Demand, kW; split core 50A CTs.
3. CSS Cooling Supply, Chilled-Water Side of Heat Exchanger
 - a. C103 and C218, Chilled-Water Flow, gpm; dual turbine insertion flowmeter and 1 in. hot tap full bore valve assembly, C103 with transmitter.
 - b. C104, Chilled-Water HE Inlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. C105, Chilled-Water HE Outlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - d. C151, CSS Cooling Supply, tons; calculated.
4. CSS Mode Status
 - a. C115, Charge Mode Status; dry contact from TES controller.
 - b. C116, Discharge Mode Status; dry contact from TES controller

- c. C117, Chiller and Discharge Mode Status; dry contact from TES controller.
 - d. C118, Chiller Mode Status; dry contact from TES controller.
5. C106, CSS Glycol Loop Flow (upstream of pump), gpm; dual turbine insertion flowmeter and 1 in. hot tap full bore valve assembly, transmitter; an additional ultrasonic flowmeter was later added after logger replacement for redundancy, C122.
6. CSS Glycol Loop
 - a. C107, Bypass Valve Exit/Pump Suction Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - b. C108, Pump Discharge/HE Inlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. C109, HE Outlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - d. C110, Cool Storage Chiller Outlet/Bypass Valve Inlet/Cool Storage Tank Inlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - e. C121, Cool Storage Tank Outlet Temperature, °F; 100 Ω RTD, transmitter, surface mounted, added later after logger replacement.
7. C123-C127, CSS Tank Capacity, %; added after logger replacement; capacitance type, later replaced with differential type, transmitter; 1 ea. in 6 tanks.
8. Centrifugal Chiller Compressor Electric Demand
 - a. C203, DR Chiller-1 Compressor-1 Electric Demand, kW; split core 600A CTs.
 - b. C204, DR Chiller-1 Compressor-2 Electric Demand, kW; split core 600A CTs.
 - c. C205, DR Chiller-2 Compressor-1 Electric Demand, kW; split core 600A CTs.
 - d. C206, DR Chiller-2 Compressor-2 Electric Demand, kW; split core 600A CTs.
9. Condenser Water Pump(s) Electric Demand (C220-ASD and C202-direct), kW; split core 100A CTs, direct with summing modules.
10. Cooling Tower Fan Electric Demand
 - a. C301, Fan 1&2 Electric Demand, kW; split core 100A CTs.
 - b. C302, Fan 3&4 Electric Demand, kW; split core 100A CTs.
11. Building Chilled-Water Pump(s) Electric Demand (C219-ASD and C201-direct), kW; split core 200A CTs, direct with summing modules.
12. Building Thermal Conditions
 - a. C221, Building Chilled-Water Return Flow, gpm; added later.
 - b. Building Chilled-Water Supply Temperature; not available.
 - c. C207, Building Chilled-Water Return Temperature, °F; RTD, transmitter, and thermowell.
 - d. Building Cooling Load, tons; calculated in spreadsheet (9.d + 10.d).
13. Cooling Load Loop #1
 - a. C208, Chilled-Water Return Flow, gpm; dual turbine insertion flowmeter, and 1 in. hot tap full bore valve assembly, transmitter.
 - b. C209, Water Return Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. C210, Chilled-Water Supply Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - d. C251, Load Loop #1 Cooling Load, tons; calculated.
14. Cooling Load Loop #2
 - a. C211, Chilled-Water Supply Flow, gpm; dual turbine insertion flowmeter, and 1 in. hot tap full bore valve assembly, transmitter.
 - b. C212, Chilled-Water Return Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. C213, Chilled-Water Supply Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - d. C252, Load Loop #2 Cooling Load, tons; calculated.
15. Centrifugal Chiller -1 Thermal Conditions
 - a. C214, Chilled-Water Outlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - b. C215, Chilled-Water Inlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. Centrifugal Chiller-1 Cooling Supply, tons; calculated in spreadsheet.
16. Centrifugal Chiller-2 Thermal Conditions
 - a. C216, Chilled-Water Outlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - b. C217, Chilled-Water Inlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. Centrifugal Chiller-2 Cooling Supply, tons; calculated in spreadsheet.
17. Cooling Tower-1 Thermal Conditions
 - a. C305, Water Inlet Flow, gpm; dual turbine insertion flowmeter, and 1 in. hot tap full bore valve assembly, transmitter; later replaced with an ultrasonic flowmeter.
 - b. C306, Water Inlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. C307, Water Outlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - d. C351, Cooling Tower-1 Heat Rejected, tons; calculated.
18. Cooling Tower-2 Thermal Conditions
 - a. C308, Water Inlet Flow, gpm; dual turbine insertion flowmeter, and 1 in. hot tap full bore valve assembly, transmitter; later replaced with an ultrasonic flowmeter.
 - b. C309, Water Inlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - c. C310, Water Outlet Temperature, °F; 100 Ω RTD, transmitter, and thermowell.
 - d. C352, Cooling Tower-2 Heat Rejected, tons; calculated.
19. C111-C114, Building Main Meter Electric Demand, kW; pulse output from 4 utility time-of-use metering relays.
20. Ambient Weather Conditions

- a. C303, Outdoor Ambient Temperature, °F; 100 Ω RTD, transmitter
- b. C304, Outdoor Relative Humidity, % RH; relative humidity sensor, transmitter.

F11. VERIFICATION OF SENSOR CALIBRATION

Once the loggers were mounted, conduit and cabling runs were completed, and all thermowells were installed, the temperature sensor function was verified utilizing a calibration oil bath and a primary standard RTD. Flowmeter function was verified utilizing both flow and heat balance.

F12. EXPERIENCE WITH THE MEASUREMENT SYSTEM/DATA VALIDATION

Temperature Sensors. System heat balances and related data validation efforts identified possible drift in the Cool Storage Tank Inlet Temperature. Cool storage capacity was tracked over time using a heat addition/subtraction calculation at each 15-min. time step. These calculations indicated an offset between calculated capacity and tank discharge temperature. It was unknown at the time whether this was an indication of standby loss (a possible 0.3 ton-hrs/0.25-hour) or measurement error. An error analysis procedure was developed using weekly data to determine the sensitivity of the results to incremental variation in the measured data. Analysis indicated that the results were well within the range of expected uncertainty.

Insertion Flowmeters. The cooling tower insertion turbine flowmeters did not last long. Within a few months of installation, they began failing and were eventually destroyed by flow conditions. They had been installed at the most reasonable location in the condenser water loops, on the vertical riser before inlet to the tower, but air and debris began to chip away at the turbines. These were initially sent back to the factory for repair and were subsequently replaced with clamp-on ultrasonic flowmeters. These meters have not provided much better service, as the high aeration levels have significantly inhibited meter function and impacted data reliability. Replacement with another type of flowmeter not sensitive to these conditions should be considered.

After two years in service, the remainder of the insertion flowmeters were removed and returned to the factory for calibration verification, re-spanning to actual conditions, and recalibrations. These sensors experienced no discernible change in calibration. A refurbished cooling tower insertion flowmeter was put into service on the building chilled-water return line. When the plant outputs cooling from the cool storage system heat exchanger, the chilled-water flow through the heat exchanger is equivalent to the sum of the load loop flows and to the building return flow within 0.5% of the reading.

Cool Storage Inventory Sensors. Outputs from the factory-installed, capacitance type, cool storage ice inventory sensors were added after data logger replacement. Data from these sensors indicated poor response to system changes. Sensors of this type tend to wick up or retain surface moisture after depletion of water (in the ice-making mode). The factory subsequently replaced them with hydrostatic level indicators (differential pressure type) that have been more stable and repeatable. Though they are vulnerable to initial adjustment if ice

is present, essentially requiring ice-free conditions, these sensors appear to function within 10% of their calculated capacity.

F13. MEASURED LONG-TERM PERFORMANCE

This section documents the facility energy-use and performance-measurement indices determined for the monitoring period. It also discusses the year-to-year variations in the thermal cooling load and provides an initial look at the impact that dynamic electricity rates had on operations.

During the April 1994–December 1997 monitoring period, the maximum measured cooling load was 1200 tons (June 25, 1995) and the average annual maximum cooling load was 1065 tons. Chilled-water plant waterside performance is dependent on the relative usage of each chiller and pumps. Monthly chilled-water plant performance has ranged from 0.9 kWh/ton-hr to 1.6 kWh/ton-hr, and annual performance has averaged 1.05 kWh/ton-hr.

Over the monitoring period, the CSS storage capacity has varied from –100 to +3400 ton-hrs (sensible plus latent). In the summer, due to increased thermal cooling load requirements, daily discharge from storage was typically limited to the amount of cooling that could be added to storage during the following daily charge cycle. On Fridays, storage was typically fully discharged, and starting Saturday morning, a 24–30 hour charge cycle was initiated. Summer storage capacity usually varied from +435 to +3000 ton-hrs (0 to 2565 ton-hrs latent). The CSS has provided approximately 15% of the cooling load in the summer, 50% in the winter, and 23% annually. Monthly CSS performance has ranged from 1.3 to 1.6 kWh/ton-hr, and annual performance has averaged 1.37 kWh/ton-hr.

Table F-1 summarizes the facility's annual electric use, maximum electric demand, maximum thermal cooling load, total annual thermal cooling load and total annual energy to meet that load, and annual chilled-water plant and cool storage system performance for the years 1995, 1996, and 1997.

Figure F-3 shows the aggregate monthly chilled-water load for the years 1995, 1996, and 1997. Aggregate monthly summer loads are about 300,000 ton-hours, or about 10,000 ton-hours for the average day. Average winter loads are about 30%–40% of those in the summer. Cool storage capacity is roughly equivalent to about 30% of the daily average load during the summer, but because of the limited ice-making capacity, only about 15% of the load can actually be shifted. During the winter, about half of the load can be shifted.

There are year-to-year variations in load within a particular month of about $\pm 20\%$ from the three-year average load for that month. These variations are due to year-to-year differences in local climate, operation conditions, and occupancy level. Because this is a convention hotel, day-to-day variations in occupancy will be substantial, but the hotel is heavily used so one would not expect appreciable variations in average monthly occupancy from year to year. Aggregate annual chilled-water loads were examined and found to have year-to-year variations of about $\pm 5\%$ around the three-year average load. Also examined were aggregate annual and monthly chilled-water loads for the two chilled-water loops in the hotel, one serving primarily guest rooms and the other primarily meeting rooms and public spaces. Year-to-year variations of these monthly loads were found to be about $\pm 20\%$ around the three-year average monthly load.

TABLE F-1 Electric Energy Use and Thermal Performance

Annual Indices	1995	1996	1997
Maximum Electric Demand	3480 kW (July)	3764 kW (May)	3307 kW (Sept.)
Electricity Use and Sales, on RTP Rate	19.7 GWh, \$1,480,000	20.5 GWh, \$1,446,000	20.23 GWh, \$1,390,000
Maximum Thermal Cooling Load	1200 tons (June) [4220 kWh _T]	998 tons (April) [3510 kWh _T]	961 tons (May) [3380 kWh _T]
Thermal Cooling Load	2,260,000 ton-hr [7.95 GWh _T]	2,600,000 ton-hr [9.14 GWh _T]	2,610,000 ton-hr [9.18 GWh _T]
Cooling Energy	2.50 GWh _E	2.70 GWh _E	2.73 GWh _E
Chilled-Water Plant Performance	1.06 kWh _E /ton-hr ^a [0.301 kWh _E / kWh _T]	1.04 kWh _E /ton-hr [0.296 kWh _E / kWh _T]	1.05 kWh _E /ton-hr [0.299 kWh _E / kWh _T]
Cool Storage System Performance	1.41 kWh _E /ton-hr ^a [0.401 kWh _E / kWh _T]	1.36 kWh _E /ton-hr [0.387 kWh _E / kWh _T]	1.34 kWh _E /ton-hr [0.381 kWh _E / kWh _T]

^a Does not include data from November 1995.

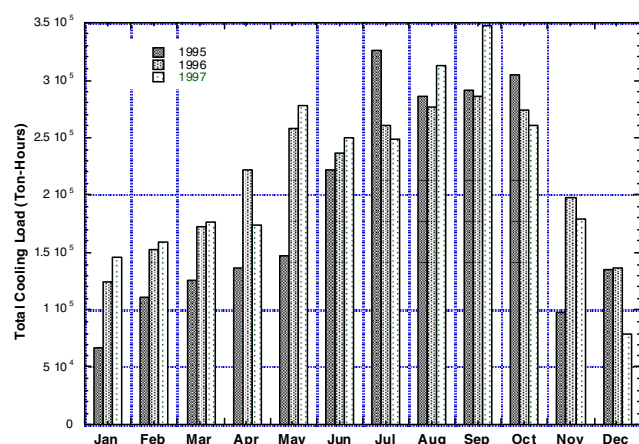


Figure F-3 Monthly total cooling load.

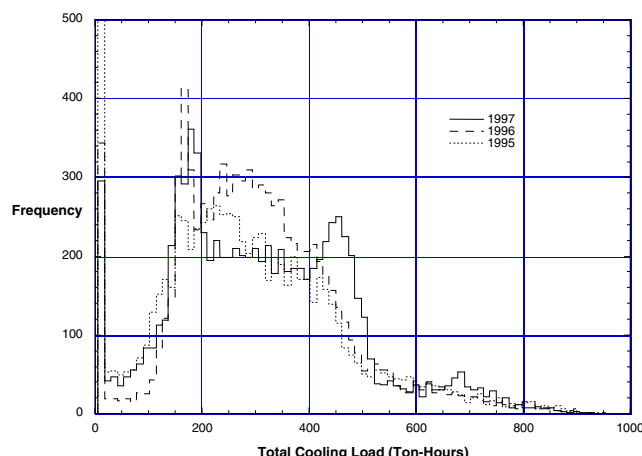


Figure F-4 Load frequency distribution plot.

Frequency distributions for the hourly chilled-water load for the years 1995, 1996, and 1997 are shown in Figure F-4. The high-load tails of the three distributions are very similar for loads greater than about 500 tons. In the intermediate load range from about 100 to 500 tons, there are large, systematic differences in the distributions. In 1995 the distribution was relatively flat, while in 1996 there was a noticeable peak in the distribution at slightly less than 200 tons and a broad peak in the region from 250 to 350 tons. In 1997 there is yet another distinct profile with the same sharp peak just below 200 tons, a flat profile at intermediate loads, and an additional peak just above 450 tons.

It should be noted that the monitoring project has had little impact on daily facility operations. At best, the more knowledgeable staff may have occasionally accessed a logger display window for instantaneous information. Monthly analysis of plant performance was provided to facility energy managers on a very limited basis. It was not until July 1996 that staff had direct access to monitoring system sensors outputs via the new BAS.

Much of the difference in the frequency distributions is believed to be the result of changes in operational practice over time. Evidence for this is that during 1995 there were about

1200 hours when the chilled-water load was zero, while in 1996 and 1997 the zero-load frequency decreased to about 300 hours. The peak at 150 to 200 tons observed in 1996 and 1997 is likely due to operation of the ice chiller in a direct cooling mode. In this mode, at loads somewhat larger than the nominal capacity of the chiller, the leaving water temperature is probably being allowed to float upwards, increasing the apparent capacity of the 150-ton machine; this technique allows the facility to avoid operation of the large chillers at loads below about 200 tons. The location of the second peak evident in the 1997 data at just over 450 tons corresponds to the capacity of the individual compressors on the large chillers, but no specific strategy has been identified that would lead to this peak in the load frequency distribution.

A three-year time period is relatively short compared to the expected lifetime of a chilled-water system. Over the life of a system, one would expect to see not only these operational changes but also the effects of technological change and of change in the business environment. The substantial variations in load-frequency distribution observed here and additional variations likely to be observed over longer time periods are

indicative of the inherent uncertainty in load that must be accounted for during design. It is not clear whether the use of typical year climate conditions and static assumptions about operating practices, both of which are common in simulation, provide a very meaningful representation of the long-term performance of a building.

F14. BUILDING PERFORMANCE

During the monitoring period from February 1994 through July 1997, the maximum measured cooling load was 1200 tons (June 25, 1995); the average annual maximum cooling load was 1100 tons. Chilled-water plant waterside performance (does not include cooling coil fan kW) is dependent on the relative usage of each chiller. It has ranged from 1.2 to 0.9 kWh/ton-hr. Over the monitoring period, the CSS storage capacity has varied from -100 to +3,200 ton-hrs (sensible plus latent). In summer, due to increased load requirements, only as much storage as could be recharged in the following daily cycle was typically discharged. Summer storage capacity usually varied from +435 to +2500 ton-hrs (0 to 2065 ton-hrs latent). The CSS has served approximately 15% of the cooling load in the summer to 50% in the winter. CSS performance has ranged from 1.3 to 1.5 kWh/ton-hr.

F15. LESSONS LEARNED

1. Projects of this type effectively teach users the limitations of their instrumentation and data management skills.

2. Many HVAC instrumentation contractors are woefully unprepared to provide high-end installation services.
3. Cooling load profiles and performance values within $\pm 5\%$ can be obtained with the assistance of a knowledgeable and helpful staff, quality HVAC sensors, a dedicated data acquisition system, and commonly used industrial calibration and installation techniques.
4. Utilizing a real-time system energy balance evaluation offers an effective method of managing instrumentation error.
5. After examining nearly four years of electric and thermal cooling load profiles, it is not clear whether use of typical year climate conditions and static assumptions about operating practices, both of which are common in simulation, provide a very meaningful representation of the long-term performance of a building.

F16. BIBLIOGRAPHY FOR APPENDIX F

- F-1 Ken Gillespie, Steven Blanc, and Steve Parker, Performance of a hotel chilled-water plant with cool storage, *ASHRAE Transactions* 105(2):117, 1999.
- F-2 Ken Gillespie, Determining the performance of a chilled-water plant, *Transactions of the 1997 Cool Sense National Forum on Integrated Chiller Retrofits, San Francisco, CA*, Lawrence Berkeley National Laboratory and Pacific Gas & Electric Company, 1997.

(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX G— EXAMPLES OF ANALYZED DATA

G1. EXAMPLE 1

Site Description: Institutional facility near Dallas, TX
Age of Chilled-Water Plant: 1999
System Type: Chillers in parallel with dedicated primary pumps/secondary pumping
Chiller: Two 1000 ton chillers with VFDs
Cooling Tower: Two open tower with 75 hp two-speed fans
Primary Chilled-Water Pump: Two constant-speed 25 hp (2080 gpm)
Secondary Chilled-Water Pump: Two pumps with VFDs
Condenser Water Pump: Two dedicated constant-speed 125 hp (3000 gpm) pumps
Monitored Points: Chiller kW, ChW Flow, ChWS Temp, ChWR Temp, CondW Flow, CondInW Temp, Cond-OutW Temp, PChW Pump kW, SChW Pump kW, CondWPump1+Cooling Tower 1, CondWPump2+Cooling Tower2, OA Temp, OA %RH, Sample Zone Temp

Monitoring Period: July 2005 through December 2005

Monitoring Comments: 1 min. data converted to 15 min. data; off and start-up conditions are not included in filtered performance calculations; secondary pump not included in any calculations; a single chiller operated during monitoring period

Average Cooling Load: 2754 kW (783 tons)

Maximum Cooling Load: 4259 kW (1211 tons)

Minimum Cooling Load: 862 kW (245 tons)

Average Plant Performance (filtered): 5.51 COP
(0.638 kW/ton)

Total Plant Performance (filtered): 5.46 COP
(0.644 kW/ton)

Total Plant Performance (unfiltered): 5.58 COP
(0.630 kW/ton)

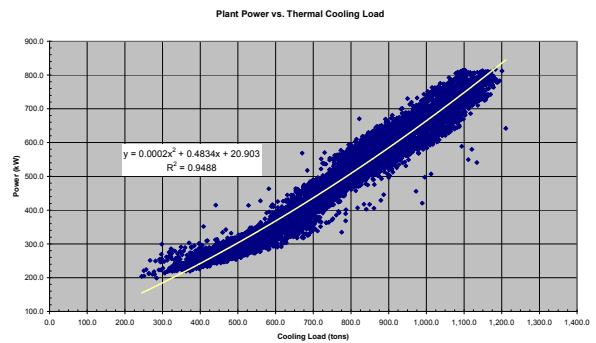
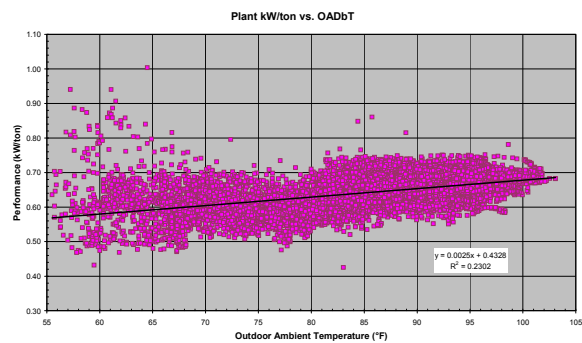
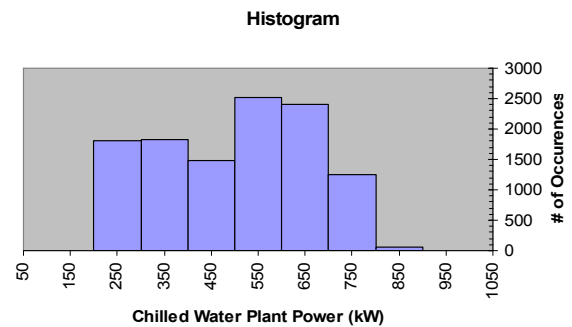
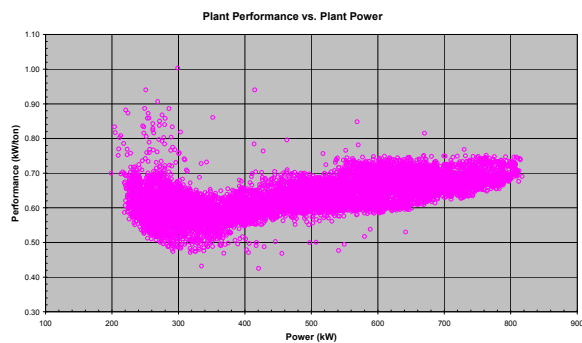
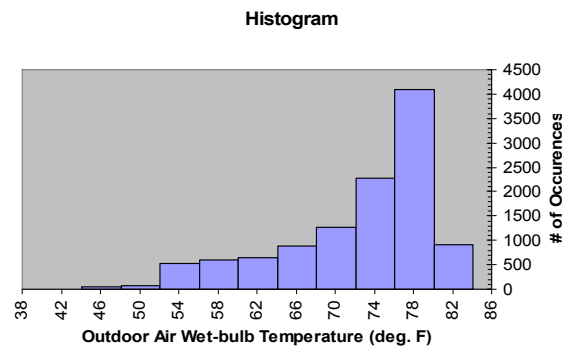
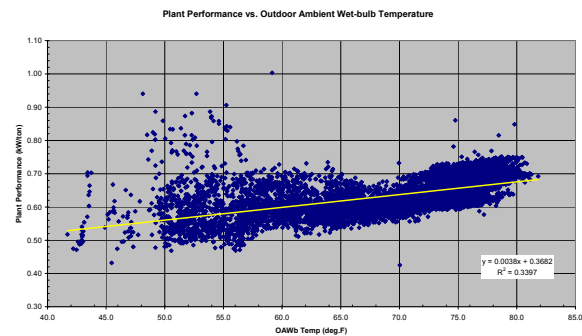
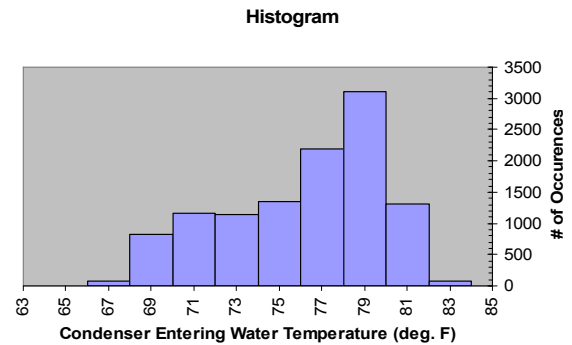
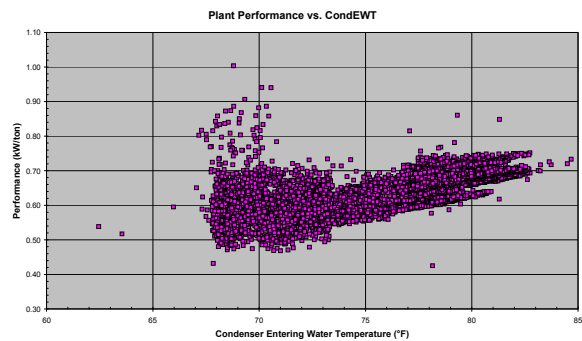
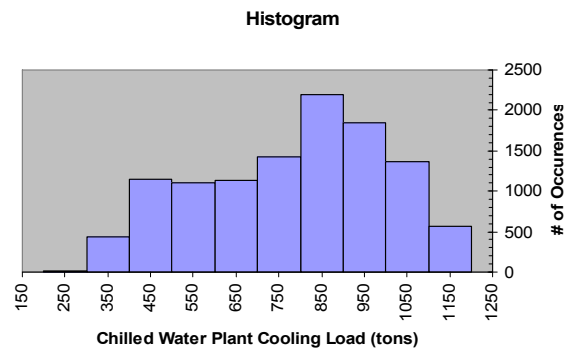
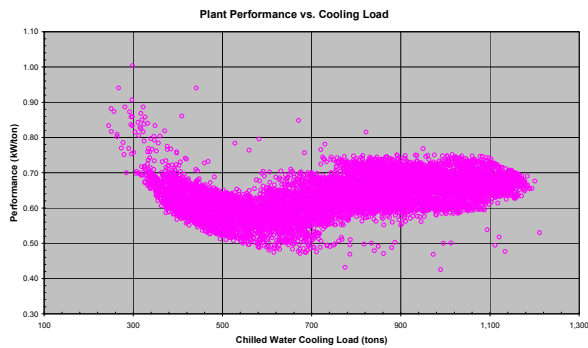
Total plant performance is total cooling energy delivered during monitoring period divided by total energy used during monitoring period. This is not the same as average plant performance, which is the average of individual time-interval performance values.

Average Condenser Entering Water Temperature:
24.5°C (76.1°F)

Average Outdoor Dry-Bulb Temperature: 28.8°C
(83.9°F)

Average Outdoor Wet-Bulb Temperature: 21.3°C
(70.3°F)

XY Plots:



G2. EXAMPLE 2

Site Description: County Center, Vista, CA

Age of Chilled-Water Plant: Chillers are 1998 vintage

System Type: All-VFD plant with primary/booster direct coupled chilled-water distribution with all three-way valves and decouplers eliminated

Chillers: Three 575-ton centrifugal chillers with VFDs

Cooling Tower: Two 850-ton towers, fans with VFDs

Primary Chilled-Water Pumps: Four 20 hp (1150 gpm) pumps with VFDs

Condenser Water Pumps: Four 60 hp (1740 gpm) pumps with VFDs

Booster Chilled-Water Pumps: Six 60 hp pumps with VFDs

Monitored Points: Total Chiller kW, Total Primary ChWPump kW, Total Cooling Tower kW, Total Booster1 ChWPump kW, Total Booster2 ChWPump kW, Total Plant kW (point 2), Total Plant Cooling tons, Total Plant kW/ton, OA Temp and OA %RH

Monitoring Periods: (1) July 27–August 4, 2005, and (2) November 2–8, 2005

Monitoring Comments: 5 min. data; outdoor ambient temperature and humidity monitored points are hourly data over a shorter period; Total Booster1 ChWPump kW and Total Booster2 ChWPump kW are included in Total Plant kW

Period #1 Results:

Average Cooling Load: 2430 kW (691 tons)

Maximum Cooling Load: 4274 kW (1215 tons)

Maximum ChWPlant Electric Load: 559 kW

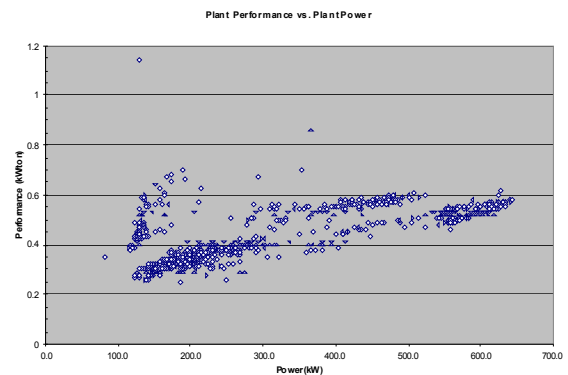
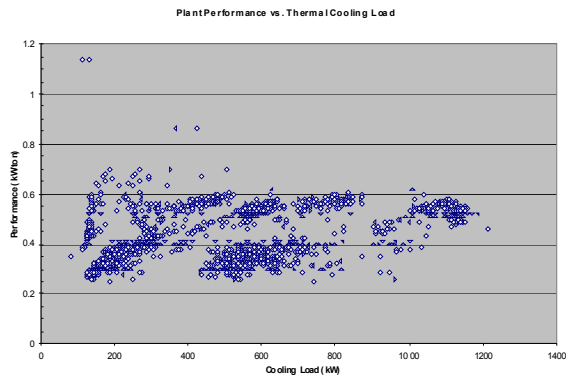
Average Plant Performance: 8.02 COP (0.438 kW/ton); before the plant retrofit project, which included a piping retrofit and implementation of demand-based controls, the annual plant efficiency was 3.25 COP (1.18 kW/ton). The project was completed in December 2003.

Total Plant Performance: 7.77 COP (0.452 kW/ton)

Average Outdoor Dry-Bulb Temperature: 21.47°C (70.64°F); 7/29, 31/2005

Average Outdoor Wet-Bulb Temperature: 19.16°C (66.48°F); 7/29, 31/2005

XY Plots:



Period #2 Results:

Average Cooling Load: 939 kW (267 tons)

Maximum Cooling Load: 2599 kW (739 tons)

Maximum ChWPlant Electric Load: 369 kW

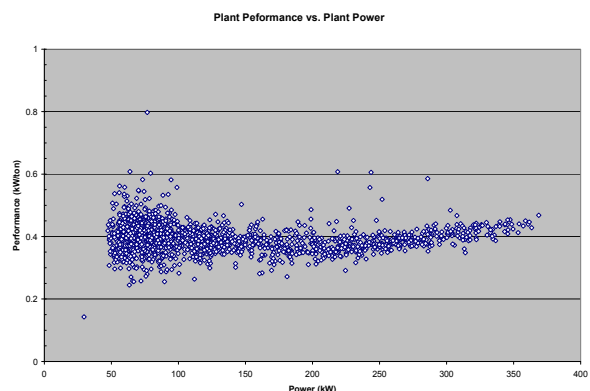
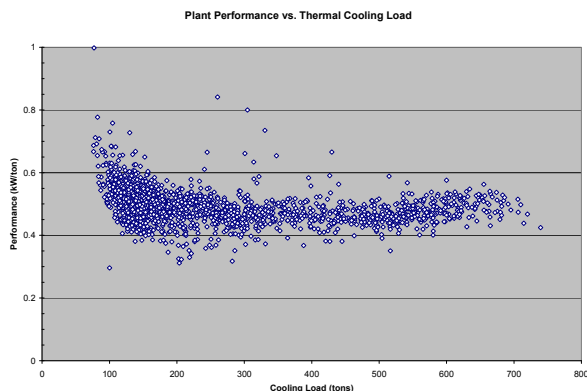
Average Plant Performance: 7.04 COP (0.499 kW/ton)

Total Plant Performance: 7.27 COP (0.483 kW/ton)

Average Outdoor Dry-Bulb Temperature: 15.07°C (59.13°F); 11/4-6/2005

Average Outdoor Wet-Bulb Temperature: 13.73°C (56.72°F); 11/4-6/2005

XY Plots:



G3. EXAMPLE 3

Site Description: Tech Center, San Ramon, CA

Age of Chilled-Water Plant: 1988

System Type: Primary only pumping with single variable-speed chiller and three-way valves at four air handlers; ChSWT with reset

Chiller: One 1988 vintage 195-ton chiller with VFD

Cooling Tower: One open tower with 15 hp two-speed fan

Primary Chilled-Water Pump: One constant-speed 10 hp (468 gpm); One air handler with 3 hp secondary booster pump

Condenser Water Pump: One constant-speed 15 hp (600 gpm, 92°F to 82°F at 71% RH)

Monitored Points: Chiller kW, ChWPlant kW, ChW Flow, ChWS Temp, ChWR Temp, ChW Pump Status, OA Temp

Monitoring Period: December 2005 through October 2006; no data in July; weather is 5 min. data

Monitoring Comments: 1 min. data converted to 15 min. data; off conditions are not included in filtered performance calculations

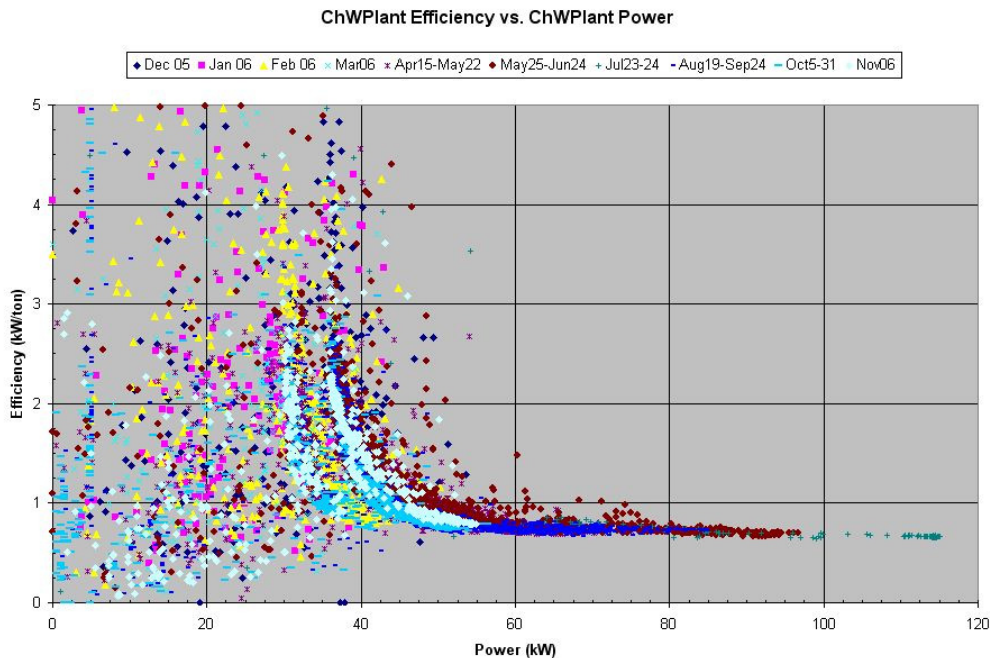
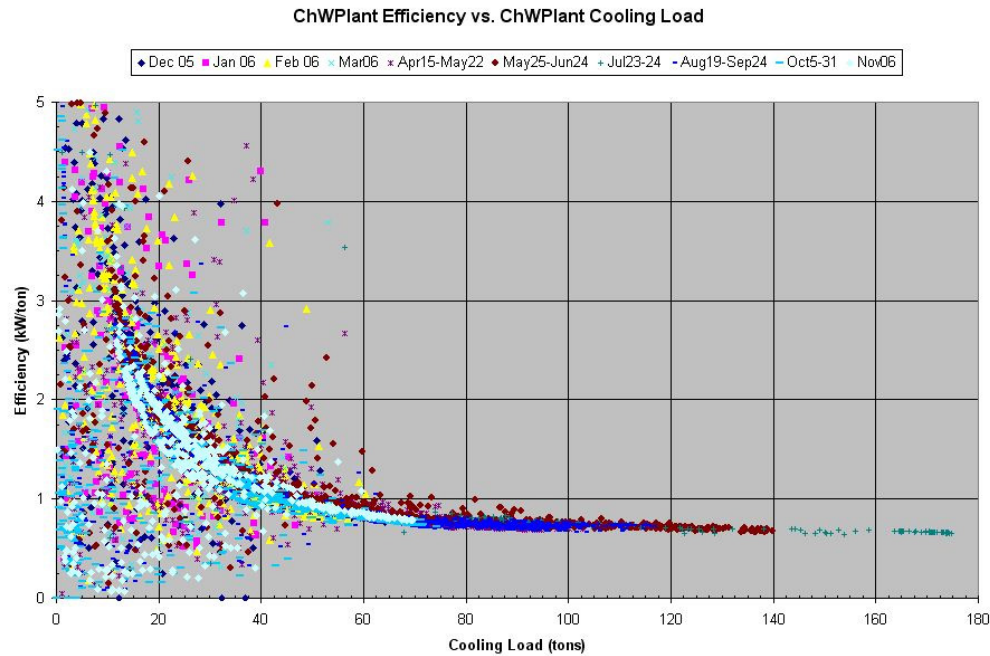
Average Cooling Load: 102.7 kW (29.2 tons)

Maximum Cooling Load: 492 kW (140 tons)

Average Plant Performance (filtered): 1.54 COP (2.28 kW/ton)

Total Plant Performance (unfiltered): 3.31 COP (1.06 kW/ton)

Average Outdoor Dry-Bulb Temperature (filtered): 16.9°C (62.5°F)



(This appendix is not part of this guideline. It is merely informative and does not contain requirements necessary for conformance to the guideline.)

INFORMATIVE APPENDIX H—BIBLIOGRAPHY

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